S1 Celestial Timekeeping and Navigation

Supplementary Chapter

LEARNING GOALS

S1.1 Astronomical Time Periods
- How do we define the day, month, year, and planetary periods?
- How do we tell the time of day?
- When and why do we have leap years?

S1.2 Celestial Coordinates and Motion in the Sky
- How do we locate objects on the celestial sphere?
- How do stars move through the local sky?
- How does the Sun move through the local sky?

S1.3 Principles of Celestial Navigation
- How can you determine your latitude?
- How can you determine your longitude?

Socrates: *Shall we make astronomy the next study? What do you say?*

Glaucon: *Certainly. A working knowledge of the seasons, months, and years is beneficial to everyone, to commanders as well as to farmers and sailors.*

Socrates: *You make me smile, Glaucon. You are so afraid that the public will accuse you of recommending unprofitable studies.*

—Plato, *Republic*

In ancient times, the practical needs for timekeeping and navigation were important reasons for the study of astronomy. The celestial origins of timekeeping and navigation are still evident. The time of day comes from the location of the Sun in the local sky, the month comes from the Moon's cycle of phases, and the year comes from the Sun's annual path along the ecliptic. The very name of the "North Star" tells us how it can be an aid to navigation.

We can now tell the time by glancing at an inexpensive electronic watch and navigate with handheld devices that receive signals from satellites of the global positioning system (GPS). But knowing the celestial basis of timekeeping and navigation can still be useful, particularly for understanding the rich history of astronomical discovery. In this chapter, we will explore the apparent motions of the Sun, Moon, and planets in greater detail, which will allow us to study the principles of celestial timekeeping and navigation.

S1.1 Astronomical Time Periods

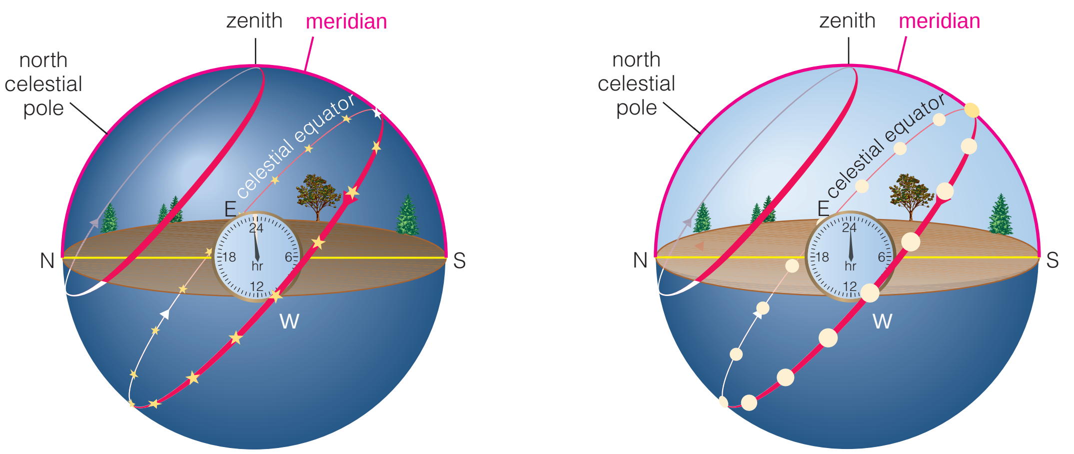
Today, our clocks and calendars are beautifully synchronized to the rhythms of the heavens. Precision measurements allow us to ensure that our clocks keep pace with the Sun's daily trek across our sky, while our calendar holds the dates of the equinoxes and solstices as steady as possible. In earlier chapters, we saw how this synchronicity took root in ancient observations of the sky. However, it is only much more recently that we have come to understand timekeeping in all its details. In this section, we will look in more depth at basic measures of time and our modern, international system of timekeeping.

How do we define the day, month, year, and planetary periods?

By now you know that the length of the day corresponds to Earth's rotation, the length of the month to the cycle of lunar phases, and the length of the year to our orbit around the Sun. However, when we look carefully at each case, we find that the correspondence is not quite as simple as we might at first guess. Instead, we are forced to define two different types of day, month, and year. We also define planetary periods in two different ways. Let's take a look at how and why we make these distinctions.

The Length of the Day We usually think of a day as the time it takes for Earth to rotate once, but if you measure this time period you'll find that it is *not* exactly 24 hours. Instead, Earth's rotation period is about 4 minutes short of 24 hours. What's going on?

We can understand the answer by thinking about the movement of the stars and Sun across our sky. Remember that the daily circling of the stars in our sky is an illusion created by Earth's rotation (see Figure 2.9). You can therefore measure Earth's rotation period by measuring how long it takes for any star to go from its highest point in the sky one day to its highest point the next day (Figure S1.1a). This time period, which we call a **sidereal day**, is about 23 hours 56 minutes (more precisely, $23^{h}56^{m}4.09^{s}$). *Sidereal* (pronounced *sy-DEAR-ee-al*) means "related to the stars"; note that you'll measure the same time no matter what star you choose. For practical purposes, the sidereal day is Earth's precise rotation period.



a A sidereal day is the time it takes any star to make a circuit of the local sky. It is about 23 hours 56 minutes.

b A solar day is measured similarly, but by timing the Sun rather than a distant star. The length of the solar day varies over the course of the year but averages 24 hours.

Figure S1.1 Using the sky to measure the length of a day.

Our 24-hour day, which we call a **solar day**, is based on the time it takes for the *Sun* to make one circuit around the local sky. You can measure this time period by measuring how long it takes the Sun to go from its highest point in the sky one day to its highest point the next day (Figure S1.1b). The solar day is indeed 24 hours on average, although it varies slightly (up to 25 seconds longer or shorter than 24 hours) over the course of a year.

A simple demonstration shows why the solar day is about 4 minutes longer than the sidereal day. Set an object to represent the Sun on a table, and stand a few steps away to represent Earth. Point at the Sun and imagine that you also happen to be pointing toward a distant star that lies in the same direction. If you rotate (counterclockwise) while standing in place, you'll again be pointing at both the Sun and the star after one full rotation (Figure S1.2a). However, because Earth rotates at the same time it orbits the Sun, you can make the demonstration more realistic by taking a couple of steps around the Sun (counterclockwise) while you rotate (Figure S1.2b). After one full rotation, you will again be pointing in the direction of the distant star, so this represents a sidereal day. But it does not represent a solar day, because you will not yet be pointing back at the Sun. If you wish to point again at the Sun, you need to make up for your orbital motion by making slightly more than one full rotation. This "extra" bit of rotation makes a solar day longer than a sidereal day.

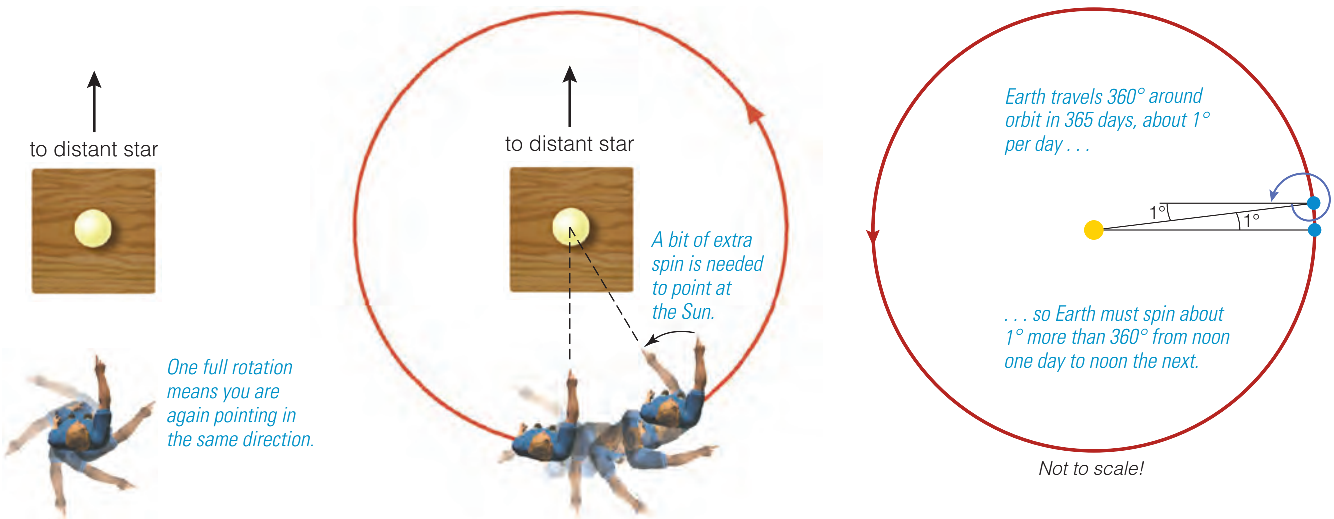
The only problem with this demonstration is that it exaggerates Earth's daily orbital motion. Because Earth takes about 365 days (1 year) to make a full 360° orbit around the Sun, Earth actually moves only about 1° per day around its orbit. Thus, a solar day represents about 361° of rotation, rather than the 360° for a sidereal day (Figure S1.2c). The extra 1° rotation takes about $\frac{1}{360}$ of Earth's rotation period, which is about 4 minutes.

The Length of the Month As we discussed in Chapter 2, our month comes from the Moon's $29\frac{1}{2}$-day cycle of phases (think "moonth"). More technically, the $29\frac{1}{2}$-day period required for each cycle of phases is called a **synodic month**. The word *synodic* comes from the Latin *synod,* which means "meeting." A synodic month gets its name because the Sun and the Moon "meet" in the sky with every new moon.

Just as a solar day is not Earth's true rotation period, a synodic month is not the Moon's true orbital period. Earth's motion around the Sun means that the Moon must complete more than one full orbit of Earth from one new moon to the next (Figure S1.3). The Moon's true orbital period, or **sidereal month**, is only about $27\frac{1}{3}$ days. Like the sidereal day, the sidereal month gets its name because it describes how long it takes the Moon to complete an orbit relative to the positions of distant stars.

The Length of the Year A year is related to Earth's orbital period, but again there are two slightly different definitions for the length of the year. The time it takes for Earth to complete one orbit relative to the stars is called a **sidereal year**. But our calendar is based on the cycle of the seasons, which we measure as the time from the spring equinox one year to the spring equinox the next year. This time period, called a **tropical year**, is about 20 minutes shorter than the sidereal year. A 20-minute difference might not seem like much, but it would make a calendar based on the sidereal year get out of sync with the seasons by 1 day every 72 years—a difference that would add up over centuries.

The difference between the sidereal year and the tropical year arises from Earth's 26,000-year cycle of axis precession [Section 2.3]. Precession not only changes the orientation of the axis in space but also changes the locations in Earth's orbit at which the seasons occur. Each year, the location of the equinoxes and solstices among the stars shifts about



a One full rotation represents a sidereal day and means that you are again pointing to the same distant star.

b While you are "orbiting" the Sun, one rotation still returns you to pointing at a distant star, but you need slightly more than one full rotation to return to pointing at the Sun.

c Earth travels about 1° per day around its orbit, so a solar day requires about 361° of rotation.

Figure S1.2 A demonstration showing why a solar day is slightly longer than a sidereal day.

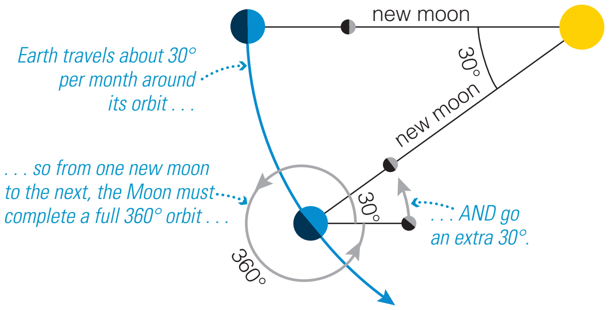


Figure S1.3 Interactive Figure The Moon completes one 360° orbit in about $27\frac{1}{3}$ days (a sidereal month), but the time from new moon to new moon is about $29\frac{1}{2}$ days (a synodic month).

$\frac{1}{26{,}000}$ of the way around the orbit. If you do the math, you'll find that $\frac{1}{26{,}000}$ of a year is about 20 minutes, which explains the 20-minute difference between the tropical year and the sidereal year.

Planetary Periods Although planetary periods are not used in our modern timekeeping, they were important to many ancient cultures. For example, the Mayan calendar was based in part on the apparent motions of Venus. In addition, Copernicus's ability to determine orbital periods of planets with his Sun-centered model played an important role in keeping the model alive long enough for its ultimate acceptance [Section 3.3].

A planet's **sidereal period** is the time the planet takes to orbit the Sun. (As usual, it has the name *sidereal* because it is measured relative to distant stars.) For example, Jupiter's sidereal period is 11.86 years, so it takes about 12 years for Jupiter to make a complete circuit around the constellations of the zodiac. Jupiter therefore appears to move through roughly one zodiac constellation each year. If Jupiter is currently in Sagittarius (as it is for much of 2008), it will be in Capricorn at this time next year and Aquarius the following year, returning to Sagittarius in 12 years.

A planet's **synodic period** is the time between when it is lined up with the Sun in our sky at one time and the next similar alignment. (As with the Moon, the term *synodic* refers to the planet's "meeting" the Sun in the sky.) Figure S1.4 shows that the situation is somewhat different for planets nearer the Sun than Earth (that is, Mercury and Venus) and planets farther away (all the rest of the planets).

Look first at the situation for the more distant planet in Figure S1.4. As seen from Earth, this planet will sometimes line up with the Sun in what we call a **conjunction**. At other special times, it will appear exactly opposite the Sun in our sky, or at **opposition**. We cannot see the planet during conjunction with the Sun because it is hidden by the Sun's glare and rises and sets with the Sun in our sky. At opposition, the planet moves through the sky like the full moon, rising at sunset, reaching the meridian at midnight, and setting at dawn. Note that the planet is closest to Earth at opposition and hence appears brightest in our sky at this time.

Now look at the planet that is *nearer* than Earth to the Sun in Figure S1.4. This planet never has an opposition but instead has two conjunctions—an "inferior conjunction" between Earth and the Sun and a "superior conjunction" when the planet appears behind the Sun as seen from Earth. Two other points are important for the inner planets: their points of **greatest elongation**, when they appear farthest from the Sun in our sky. At its greatest eastern elongation, Venus appears about 46° east of the Sun in our sky, which means it shines brightly in the evening. Similarly, at its greatest western elongation, Venus appears about 46° west of the Sun and shines brightly before dawn. In between the times when Venus appears in the morning sky and the times when it appears in the evening sky, Venus disappears from view for a few weeks with each conjunction. Mercury's pattern is similar, but because it is closer to the Sun, it never appears more than about 28° from the Sun in our sky. That makes Mercury difficult to see, because it is almost always obscured by the glare of the Sun.

THINK ABOUT IT

Do we ever see Mercury or Venus at midnight? Explain.

As you study Figure S1.4, you might wonder whether Mercury or Venus ever falls directly in front of the Sun at inferior conjunction, creating mini-eclipses as they block a little of the Sun's light. They do, but only rarely, because

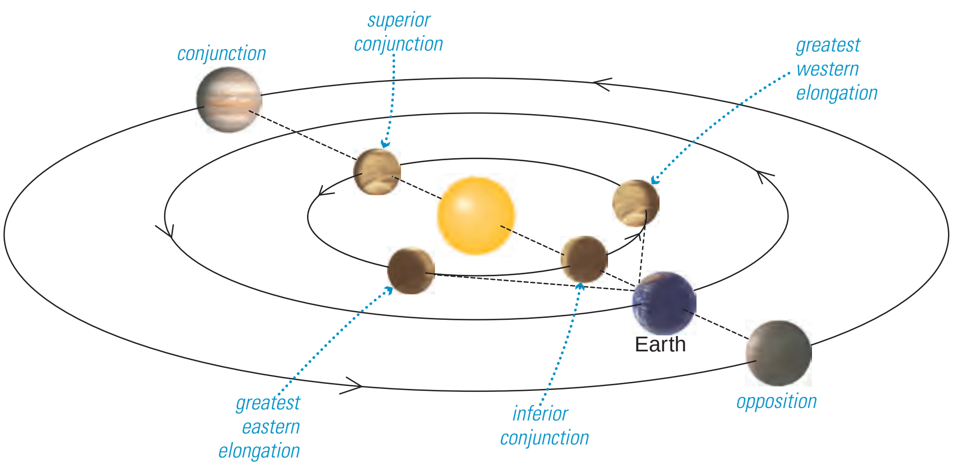


Figure S1.4 This diagram shows important positions of planets relative to Earth and the Sun. For a planet farther from the Sun than Earth (such as Jupiter), conjunction occurs when the planet appears aligned with the Sun in the sky, and opposition occurs when the planet appears on our meridian at midnight. Planets nearer the Sun (such as Venus) have two conjunctions and never get farther from the Sun in our sky than at their greatest elongations. (Adapted from *Advanced Skywatching,* by Burnham et al.)

their orbital planes are slightly tilted compared to Earth's orbital plane (the ecliptic plane). As a result, Mercury and Venus usually appear slightly above or below the Sun at inferior conjunction. But on rare occasions, we do indeed see Mercury or Venus appear to pass directly across the face of the Sun during inferior conjunction (Figure S1.5). Such events are called **transits**. Mercury transits occur an average of a dozen times per century, with the first two of this century on November 8, 2006, and May 9, 2016. Venus transits come in pairs 8 years apart, with more than a century between the second of one pair and the first of the next. We are currently between the two transits of a pair: The first occurred on June 8, 2004, and the second will occur on June 6, 2012. After that, it will be 105 years until the first of the next pair of Venus transits, which will occur in 2117 and 2125.

How do we tell the time of day?

Telling time seems simple, but in fact there are several different ways to define the time of day, even after we agree that time should be based on the 24-hour solar day. Let's explore some of the ways of telling time and see how they ultimately led to our modern system in which we can synchronize clocks anywhere in the world.

Apparent Solar Time If we base time on the Sun's *actual* position in the local sky, as is the case when we use a sundial (Figure S1.6), we are measuring **apparent solar time**. Noon is the precise moment when the Sun is highest in the sky (on the meridian) and the sundial casts its shortest shadow. Before noon, when the Sun is rising upward through the sky, the apparent solar time is *ante meridiem* ("before

MATHEMATICAL INSIGHT S1.1 The Copernican Layout of the Solar System

As discussed in Chapter 3, Copernicus favored the Sun-centered model partly because it allowed him to calculate orbital periods and distances for the planets. Let's see how the Copernican system allows us to determine orbital (sidereal) periods of the planets.

We cannot directly measure orbital periods, because our own movement around the Sun means that we look at the planets from different points in our orbit at different times. However, we can measure synodic periods simply by seeing how much time passes between one particular alignment (such as opposition or inferior conjunction) and the next. Figure 1 shows the geometry for a planet *farther from the Sun than Earth* (such as Jupiter), under the assumption of circular orbits (which is what Copernicus assumed). Study the figure carefully to notice the following key facts:

- The dashed brown curve shows the planet's complete orbit. The time the planet requires for one complete orbit is its orbital (sidereal) period, P_{orb}.
- The solid brown arrow shows how far the planet travels along its orbit from one opposition to the next. The time between oppositions is defined as its synodic period, P_{syn}.
- The dashed blue curve shows Earth's complete orbit; Earth takes $P_{Earth} = 1$ yr to complete an orbit.
- The solid red curve (and red arrow) shows how far Earth goes during the planet's synodic period; it is *more* than one complete orbit because Earth must travel a little "extra" to catch back up with the other planet. The time it takes Earth to travel the "extra" distance (the thick part of the red curve) must be the planet's synodic period minus 1 year, or $P_{syn} - 1$ yr.
- The angle that the planet sweeps out during its synodic period is equal to the angle that Earth sweeps out as it travels the "extra" distance. Thus, the *ratio* of the planet's complete orbital period (P_{orb}) to its synodic period (P_{syn}) must be equal to the *ratio* of Earth's orbital period (1 yr) to the time required for the "extra" distance (see Appendix C.5 for a review of ratios). Since we already found that the time required for this extra distance is $P_{syn} - 1$ yr, we write:

$$\frac{P_{orb}}{P_{syn}} = \frac{1\text{ yr}}{(P_{syn} - 1\text{ yr})}$$

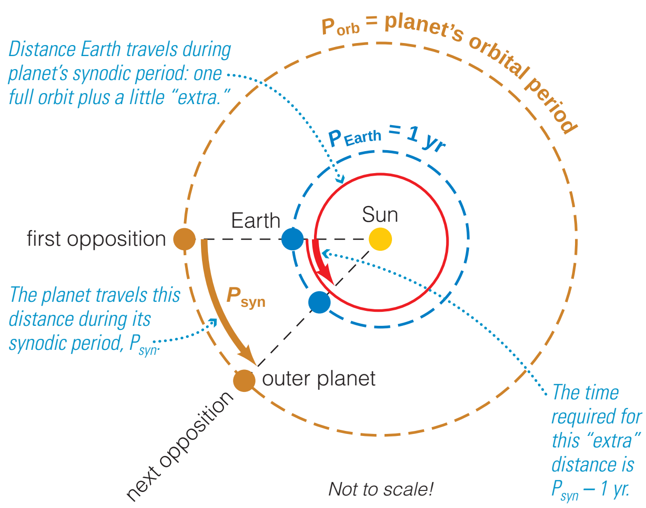


Figure 1

Multiplying both sides by P_{syn} gives us the final equation:

$$P_{orb} = P_{syn} \times \frac{1\text{ yr}}{(P_{syn} - 1\text{ yr})}$$

[for planets farther from the Sun than Earth]

The geometry is slightly different when Earth is the outer planet, as shown in Figure 2. In this case the two equal ratios are $1\text{ yr}/P_{syn} = P_{orb}/(P_{syn} - P_{orb})$. With a little algebra, you can solve this equation for P_{orb}:

$$P_{orb} = P_{syn} \times \frac{1\text{ yr}}{(P_{syn} + 1\text{ yr})}$$

[for planets closer to the Sun than Earth]

Copernicus knew the synodic periods of the planets and was therefore able to use the above equations (in a slightly different form) to calculate their true orbital periods. He was then able to use the geometry of planetary alignments to compute the dis-

Figure S1.5 This photo was taken in Florida during the transit of Venus on June 8, 2004. Venus is the small black dot near the right edge of the Sun's face.

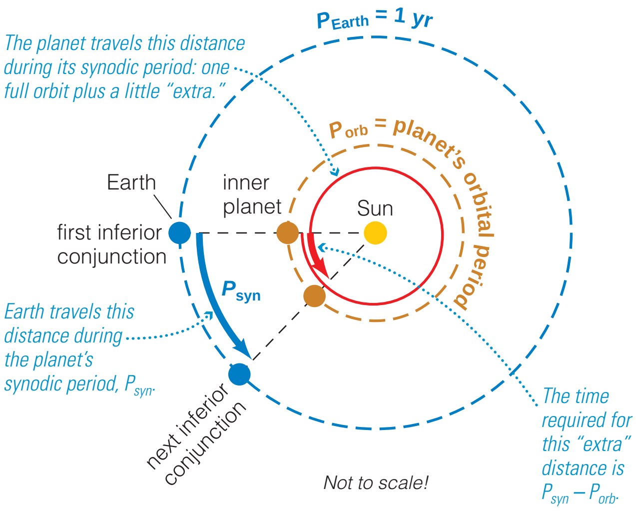


Figure 2

tances to the planets in terms of the Earth-Sun distance. (That is, he calculated distances in AU, but he did not have a method for determining how far the Earth is from the Sun.) His results, which were quite close to modern values, made so much sense to him that he felt he must have uncovered some deep truth about nature.

Example 1: Jupiter's synodic period is 398.9 days, or 1.092 years. What is its actual orbital period?

Solution:

Step 1 Understand: We are given Jupiter's synodic period (P_{syn} in the above equations) and are asked to find its orbital period (P_{orb}). Because Jupiter is farther from the Sun than Earth, we can use the first equation.

Step 2 Solve: We use the equation for a planet farther from the Sun than Earth with $P_{syn} = 1.092$ yr (Jupiter's synodic period):

$$\begin{aligned} P_{orb} &= P_{syn} \times \frac{1\text{ yr}}{(P_{syn} - 1\text{ yr})} \\ &= 1.092\text{ yr} \times \frac{1\text{ yr}}{(1.092\text{ yr} - 1\text{ yr})} \\ &= 11.87\text{ yr} \end{aligned}$$

Step 3 Explain: We have found that Jupiter's orbital period is 11.87 years. In other words, simply by measuring the time that passes from when Jupiter is opposite the Sun in one year to when it is again opposite the next year (which is Jupiter's synodic period), we have learned that Jupiter takes a little less than 12 years to orbit the Sun. Notice that the answer makes sense in that it is longer than Earth's orbital period of 1 year, just as we expect for a planet that is farther than Earth from the Sun.

Example 2: Venus's synodic period is 583.9 days. What is its actual orbital period?

Solution:

Step 1 Understand: We are given Venus's synodic period, $P_{syn} = 583.9$ days, and are asked to find its orbital period. Because Venus is closer to the Sun than Earth, we need the second equation. Also, because we are given Venus's synodic period in days, for unit consistency we need to convert it to years; you should confirm that 583.9 days $=$ 1.599 yr.

Step 2 Solve: We simply plug the value of P_{syn} into the equation for a planet closer to the Sun than Earth:

$$\begin{aligned} P_{orb} &= P_{syn} \times \frac{1\text{ yr}}{(P_{syn} + 1\text{ yr})} \\ &= 1.599\text{ yr} \times \frac{1\text{ yr}}{(1.599\text{ yr} + 1\text{ yr})} \\ &= 0.6152\text{ yr} \end{aligned}$$

Step 3 Explain: We have found that Venus takes 0.6152 year to orbit the Sun. This number is easier to interpret if we convert it to days or months; you should confirm that it is equivalent to 224.7 days, or about $7\frac{1}{2}$ months. Notice that the answer makes sense in that it is shorter than Earth's orbital period of 1 year, just as we expect for a planet that is closer than Earth to the Sun.

Figure S1.6 A basic sundial consists of a dial marked by numerals, and a stick, or *gnomon*, that casts a shadow. Here, the shadow is on the Roman numeral III, indicating that the apparent solar time is 3:00 P.M. (The portion of the dial without numerals represents nighttime hours.) Because the Sun's path across the local sky depends on latitude, a particular sundial will be accurate only for a particular latitude.

the middle of the day"), or A.M. For example, if the Sun will reach the meridian 2 hours from now, the apparent solar time is 10 A.M. After noon, the apparent solar time is *post meridiem* ("after the middle of the day"), or P.M. If the Sun crossed the meridian 3 hours ago, the apparent solar time is 3 P.M. Note that, technically, noon and midnight are *neither* A.M. nor P.M. However, by convention we usually say that noon is 12 P.M. and midnight is 12 A.M.

THINK ABOUT IT

Is it daytime or nighttime at 12:01 A.M.? 12:01 P.M.? Explain.

Mean Solar Time Suppose you set a clock to precisely 12:00 when a sundial shows noon today. If every solar day were precisely 24 hours, your clock would always remain synchronized with the sundial. However, while 24 hours is the *average* length of the solar day, the actual length of the solar day varies throughout the year. As a result, your clock will not remain perfectly synchronized with the sundial. For example, your clock is likely to read a few seconds before or after 12:00 when the sundial reads noon tomorrow, and within a few weeks your clock time may differ from the apparent solar time by several minutes. Your clock (assuming it is accurate) will again be synchronized with the Sun on the same date next year, since it keeps track of the average length of the solar day.

If we average the differences between the time a clock would read and the time a sundial would read, we can define **mean solar time** (*mean* is another word for *average*). A clock set to mean solar time reads 12:00 each day at the time that the Sun crosses the meridian *on average*. The actual mean solar time at which the Sun crosses the meridian varies over the course of the year in a fairly complex way (see "Solar Days and the Analemma," p. 100). The result is that, on any given day, a clock set to mean solar time may read anywhere from about 17 minutes before noon to 15 minutes after noon (that is, from 11:43 A.M. to 12:15 P.M.) when a sundial indicates noon.

Although the lack of perfect synchronization with the Sun might at first sound like a drawback, mean solar time is actually more convenient than apparent solar time (the sundial time)— as long as you have access to a mechanical or electronic clock. Once set, a reliable mechanical or electronic clock can always tell you the mean solar time. In contrast, precisely measuring apparent solar time requires a sundial, which is useless at night or when it is cloudy.

Like apparent solar time, mean solar time is a *local* measure of time. That is, it varies with longitude because of Earth's west-to-east rotation. For example, clocks in New York are set 3 hours ahead of clocks in Los Angeles. If clocks were set precisely to local mean solar time, they would vary even over relatively short east-west distances. For example, mean solar clocks in central Los Angeles would be about 2 minutes behind mean solar clocks in Pasadena, because Pasadena is slightly to the east.

Standard, Daylight, and Universal Time Clocks displaying mean solar time were common during the early history of the United States. However, by the late 1800s, the growth of railroad travel made the use of mean solar time increasingly problematic. Some states had dozens of different "official" times, usually corresponding to mean solar time in dozens of different cities, and each railroad company made schedules according to its own "railroad time." The many time systems made it difficult for passengers to follow the scheduling of trains.

On November 18, 1883, the railroad companies agreed to a new system that divided the United States into four time zones, setting all clocks within each zone to the same time. That was the birth of **standard time**, which today divides the world into time zones (Figure S1.7). Depending on where you live within a time zone, your standard time may vary somewhat from your mean solar time. In principle, the standard time in a particular time zone is the mean solar time in the *center* of the time zone, so that local mean solar time within a 1-hour-wide time zone would never differ by more than a half-hour from standard time. However, time zones often have unusual shapes to conform to social, economic, and political realities, so larger variations between standard time and mean solar time sometimes occur.

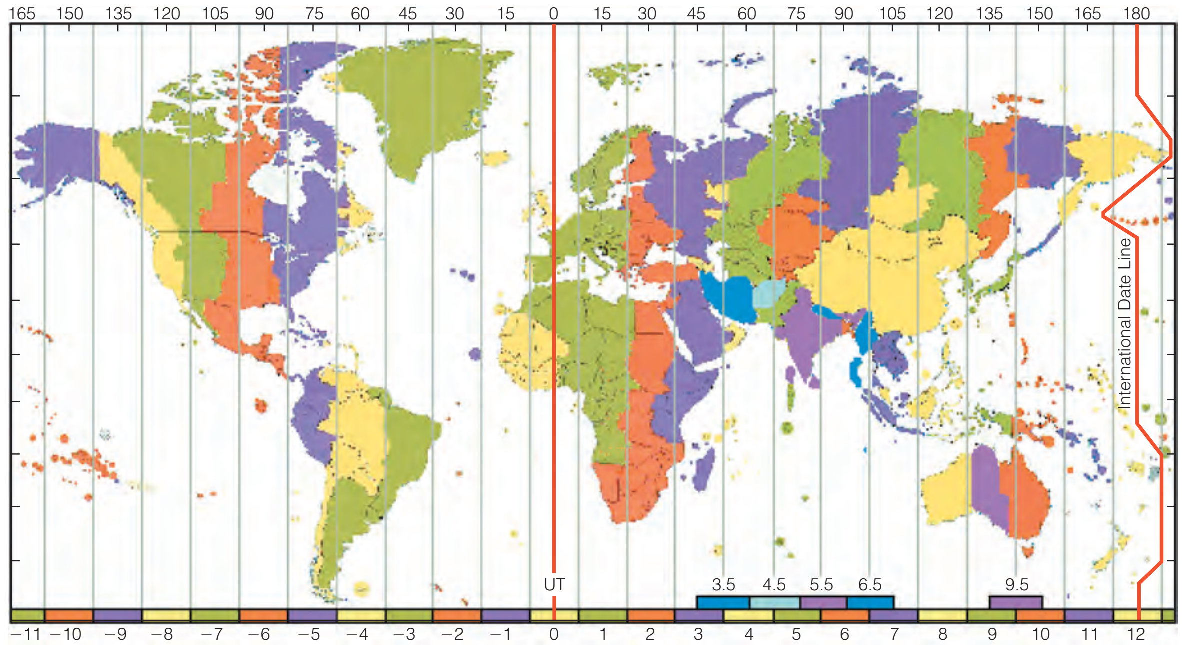


Figure S1.7 Time zones around the world. The numerical scale at the bottom shows hours ahead of (positive numbers) or behind (negative numbers) the time in Greenwich, England; the scale at the top is longitude. The vertical lines show standard time zones as they would be in the absence of political considerations. The color-coded regions show the actual time zones. Note, for example, that all of China uses the same standard time, even though the country is wide enough to span several time zones. Note also that a few countries use time zones centered on a half-hour (the upper set of four colored bars), rather than an hour, relative to Greenwich time.

In most parts of the United States, clocks are set to standard time for only part of the year. Between the second Sunday in March and the first Sunday in November,* most of the United States changes to **daylight saving time**, which is 1 hour ahead of standard time. Because of the 1-hour advance with daylight saving time, clocks read around 1 P.M. (rather than around noon) when the Sun is on the meridian.

For purposes of navigation and astronomy, it is useful to have a single time for the entire Earth. For historical reasons, this "world" time was chosen to be the mean solar time in Greenwich, England—the place that also defines longitude 0° (see Figure 2.11). Today, this *Greenwich mean time* (*GMT*) is often called **universal time (UT)**. (Outside astronomy, it is more commonly called *universal coordinated time* [UTC]. Many airlines and weather services call it "Zulu time," because Greenwich's time zone is designated "Z" and "zulu" is a common way of phonetically identifying the letter *Z*.)

MA Seasons Tutorial, Lesson 2

When and why do we have leap years?

Our modern calendar is based on the length of the tropical year, which is the amount of time from one spring equinox to the next. The calendar is therefore designed to stay synchronized with the seasons. Getting this synchronization just right was a long process in human history.

The origins of our modern calendar go back to ancient Egypt. By 4200 B.C., the Egyptians were using a calendar that counted 365 days in a year. However, because the length of a year is about $365\frac{1}{4}$ days (rather than exactly 365 days), the Egyptian calendar drifted out of phase with the seasons by about 1 day every 4 years. For example, if the spring equinox occurred on March 21 one year, 4 years later it occurred on March 22, 4 years after that on March 23, and so on. Over many centuries, the spring equinox moved through many different months. To keep the seasons and the calendar synchronized, Julius Caesar decreed the adoption of a new calendar in 46 B.C. This *Julian calendar* introduced the concept of **leap year**: Every fourth year has 366 days, rather than 365, so that the average length of the calendar year is $365\frac{1}{4}$ days.

The Julian calendar originally had the spring equinox falling around March 24. If it had been perfectly synchronized with the tropical year, this calendar would have ensured that the spring equinox occurred on the same date every 4 years (that is, every leap-year cycle). It didn't work perfectly, however, because a tropical year is actually about 11 minutes short of $365\frac{1}{4}$ days. As a result, the moment of the spring equinox slowly advanced by an average of 11 minutes per year. By the late 1500s, the spring equinox was occurring on March 11.

Concerned by this drift in the date of the spring equinox, Pope Gregory XIII introduced a new calendar in 1582. This *Gregorian calendar* was much like the Julian calendar,

*These dates for daylight saving time took effect in 2007 (thanks to legislation passed in 2005); before that, daylight saving time ran between the first Sunday in April and the last Sunday in October.

with two important adjustments. First, Pope Gregory decreed that the day in 1582 following October 4 would be October 15. By eliminating the 10 dates from October 5 through October 14, 1582, he pushed the date of the spring equinox in 1583 from March 11 to March 21. (He chose March 21 because it was the date of the spring equinox in A.D. 325, which was the time of the Council of Nicaea, the first ecumenical council of the Christian church.) Second, the Gregorian calendar added an exception to the rule of having leap year every 4 years: Leap year is skipped when a century changes (for example, in years 1700, 1800, 1900) *unless* the century year is divisible by 400. Thus, 2000 was a leap year because it is divisible by 400 ($2{,}000 \div 400 = 5$), but 2100 will *not* be a leap year. These adjustments make the average length of the Gregorian calendar year almost exactly the same as the actual length of a tropical year, which ensures

SPECIAL TOPIC Solar Days and the Analemma

The average length of a solar day is 24 hours, but the precise length varies over the course of the year. Two effects contribute to this variation.

The first effect arises from Earth's varying orbital speed. Recall that, in accord with Kepler's second law, Earth moves slightly faster when it is closer to the Sun in its orbit and slightly slower when it is farther from the Sun. Thus, Earth moves slightly farther along its orbit each day when it is closer to the Sun. This means that the solar day requires more than the average amount of "extra" rotation (see Figure S1.2) during these periods—making these solar days longer than average. Similarly, the solar day requires less than the average amount of "extra" rotation when it is in the portion of its orbit farther from the Sun—making these solar days shorter than average.

The second effect arises from the tilt of Earth's axis, which causes the ecliptic to be inclined by $23\frac{1}{2}°$ to the celestial equator on the celestial sphere. Because the length of a solar day depends on the Sun's apparent *eastward* motion along the ecliptic, the inclination would cause solar days to vary in length even if Earth's orbit were perfectly circular. To see why, suppose the Sun appeared to move exactly 1° per day along the ecliptic. Around the times of the solstices, this motion would be entirely eastward, making the solar day slightly longer than average. Around the times of the equinoxes, when the motion along the ecliptic has a significant northward or southward component, the solar day would be slightly shorter than average.

Together, the two effects make the actual length of solar days vary by up to about 25 seconds (either way) from the 24-hour average. Because the effects accumulate at particular times of year, the apparent solar time can differ by as much as 17 minutes from the mean solar time. The net result is often depicted visually by an **analemma** (Figure 1), which looks much like a figure 8. You'll find an analemma printed on many globes (Figure 2.16 shows a photographic version).

By using the horizontal scale on the analemma (Figure 1), you can convert between mean and apparent solar time for any date. (The vertical scale shows the declination of the Sun, which is discussed in Section S1.2.) For example, the dashed line shows that on November 10, a mean solar clock is about 17 minutes "behind the Sun," or behind apparent solar time. Thus, if the apparent solar time is 6:00 P.M. on November 10, the mean solar time is only 5:43 P.M. The discrepancy between mean and apparent solar times is called the **equation of time**. It is often plotted as a graph (Figure 2), which gives the same results as reading from the analemma.

The discrepancy between mean and apparent solar time also explains why the times of sunrise and sunset don't follow seasonal patterns perfectly. For example, the winter solstice around December 21 has the shortest daylight hours (in the Northern Hemisphere), but the earliest sunset occurs around December 7, when the Sun is still well "behind" mean solar time.

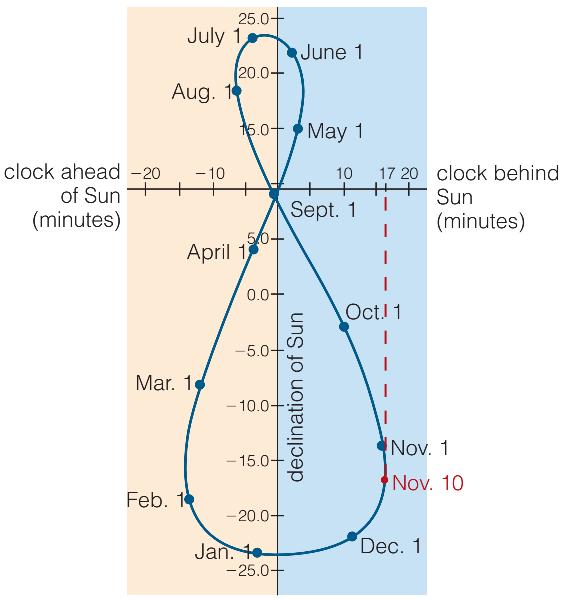


Figure 1 The analemma shows the annual pattern of discrepancies between apparent and mean solar time. For example, the dashed red line shows that on November 10, a mean solar clock reads 17 minutes behind (earlier than) apparent solar time.

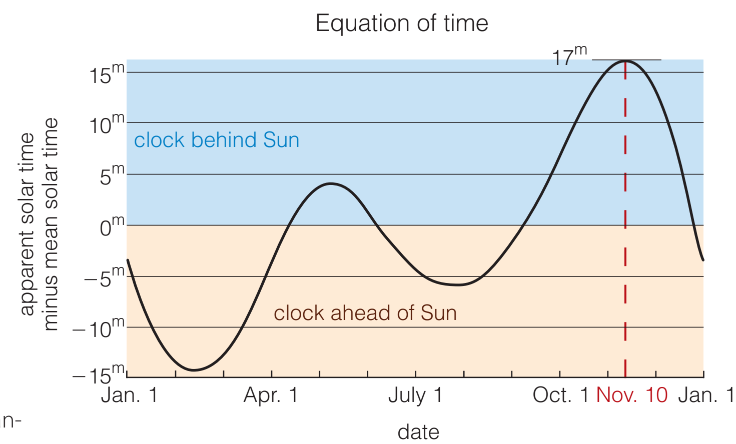


Figure 2 The discrepancies can also be plotted on a graph as the equation of time.

that the spring equinox will occur on March 21 every fourth year for thousands of years to come.

Today, the Gregorian calendar is used worldwide for international communication and commerce. (Many countries still use traditional calendars, such as the Chinese, Islamic, and Jewish calendars, for cultural purposes.) However, as you might guess, the pope's decree was not immediately accepted in regions not bound to the Catholic Church. For example, the Gregorian calendar was not adopted in England or in the American colonies until 1752, and it was not adopted in China until 1912 or in Russia until 1919.

S1.2 Celestial Coordinates and Motion in the Sky

We are now ready to turn our attention from timekeeping to navigation. The goal of celestial navigation is to use the Sun and the stars to find our position on Earth. Before we can do that, we need to understand the apparent motions of the sky in more detail than we covered in Chapter 2. We'll begin in this section by discussing how we locate objects on the celestial sphere, which will then allow us to explore how positions on the celestial sphere determine motion in the local sky. With this background, we'll be ready to explore the principles of celestial navigation in the final section of this chapter.

How do we locate objects on the celestial sphere?

Recall from Chapter 2 that the celestial sphere is an illusion, but one that is quite useful when looking at the sky. We can make the celestial sphere even more useful by giving it a set of **celestial coordinates** that function much like the coordinates of latitude and longitude on Earth. Just as we can locate a city on Earth by its latitude and longitude, we will use an object's celestial coordinates to describe its precise location on the celestial sphere.

We have already discussed the basic features of the celestial sphere that will serve as starting points for our coordinate system: the north and south celestial poles, the celestial equator, and the ecliptic. Figure S1.8 shows these locations on a schematic diagram. The arrow along the ecliptic indicates the direction in which the Sun appears to move over the course of each year. It is much easier to visualize the celestial sphere if you make a model with a simple plastic ball. Use a felt-tip pen to mark the north and south celestial poles on your ball, and then add the celestial equator and the ecliptic. Note that the ecliptic crosses the celestial equator on opposite sides of the celestial sphere at an angle of $23\frac{1}{2}°$ (because of the tilt of Earth's axis).

Equinoxes and Solstices Remember that the equinoxes and solstices are special moments in the year that help define the seasons [Section 2.2]. For example, the *spring equinox,* which occurs around March 21 each year, is the moment when spring begins for the Northern Hemisphere and fall begins for the Southern Hemisphere. These moments correspond to positions in Earth's orbit (see Figure 2.15) and hence to apparent locations of the Sun along the ecliptic. As shown in Figure S1.8, the spring equinox occurs when the Sun is on the ecliptic at the point where it crosses from south of the celestial equator to north of the celestial equator. This point is also called the spring equinox. Thus, the term *spring equinox* has a dual meaning: It is the *moment* when spring begins and also the *point* on the ecliptic at which the Sun appears to be located at that moment.

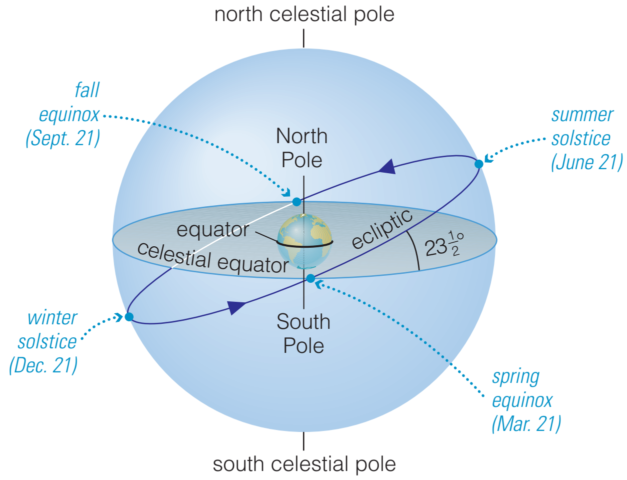


Figure S1.8 Schematic diagram of the celestial sphere, shown without stars. As a study aid, you should use a plastic ball as a model of the celestial sphere, marking it with the same special locations.

Figure S1.8 also shows the points marking the summer solstice, fall equinox, and winter solstice, with the dates on which the Sun appears to be located at each point. Remember that the dates are approximate because of the leap-year cycle and because a tropical year is not exactly $365\frac{1}{4}$ days. (For example, the spring equinox may occur anytime between about March 20 and March 23.)

Although no bright stars mark the locations of the equinoxes or solstices among the constellations, you can find them with the aid of nearby bright stars (Figure S1.9). For example, the spring equinox is located in the constellation Pisces and can be found with the aid of the four bright stars in the Great Square of Pegasus. Of course, when the Sun is located at this point around March 21, we cannot see Pisces or Pegasus because they are close to the Sun in our daytime sky.

SEE IT FOR YOURSELF

Using your plastic ball as a model of the celestial sphere (which you have already marked with the celestial poles, equator, and ecliptic), mark the locations and approximate dates of the equinoxes and solstices. Based on the dates for these points, approximately where along the ecliptic is the Sun on April 21? On November 21? How do you know?

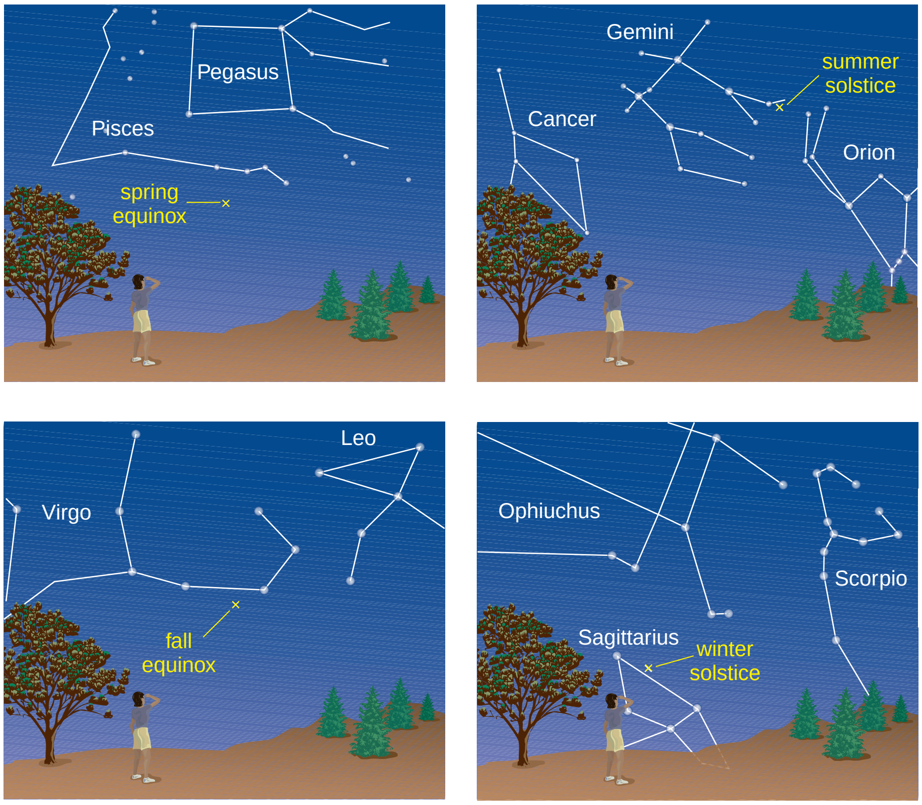


Figure S1.9 These diagrams show the locations among the constellations of the equinoxes and solstices. No bright stars mark any of these points, so you must find them by studying their positions relative to recognizable patterns. The time of day and night at which each point is above the horizon depends on the time of year.

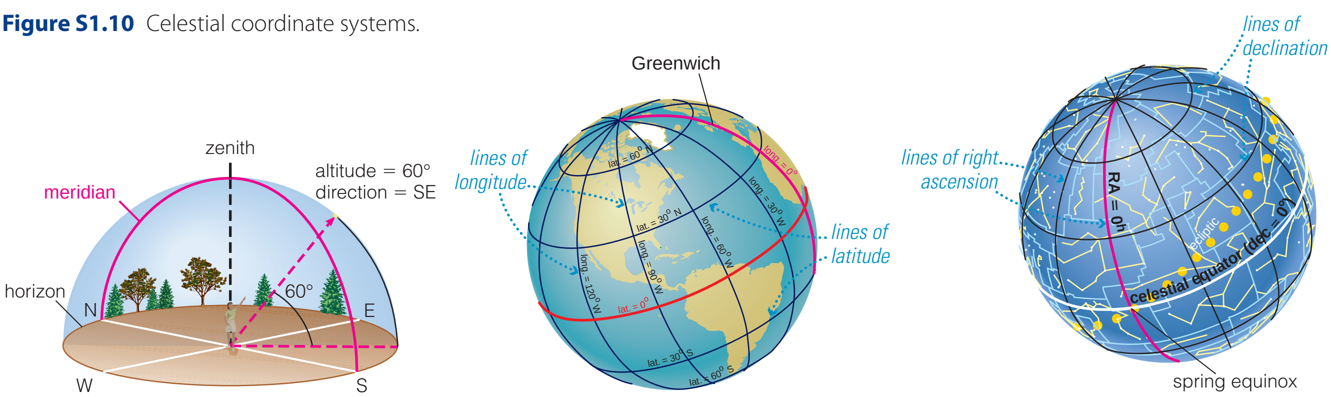
Celestial Coordinates We can now add our system of celestial coordinates to the celestial sphere. Because this will be the third coordinate system we've used in this book, it's easier to understand if we first review the other two. Figure S1.10a shows the coordinates of *altitude* and *direction* (or *azimuth**) we use in the local sky. Figure S1.10b shows the coordinates of *latitude* and *longitude* we use on Earth's surface. Finally, Figure S1.10c shows our new system of celestial coordinates. As you can see in the figure, these coordinates are called **declination (dec)** and **right ascension (RA)**.

*Azimuth is usually measured clockwise around the horizon from due north. By this definition, the azimuth of due north is 0°, of due east is 90°, of due south is 180°, and of due west is 270°.

If you compare Figures S1.10b and c, you'll see that declination on the celestial sphere is similar to latitude on Earth and right ascension is similar to longitude. Let's start with declination; notice the following key points:

- Just as lines of latitude are parallel to Earth's equator, lines of declination are parallel to the celestial equator.
- Just as Earth's equator has lat = 0°, the celestial equator has dec = 0°.
- Latitude is labeled *north* or *south* relative to the equator, while declination is labeled *positive* or *negative*. For example, the North Pole has lat = 90°N, while the north celestial pole has dec = +90°; the South Pole has lat = 90°S, while the south celestial pole has dec = −90°.

Figure S1.10 Celestial coordinate systems.



a We use altitude and direction to pinpoint locations in the local sky.

b We use latitude and longitude to pinpoint locations on Earth.

c We use declination and right ascension to pinpoint locations on the celestial sphere.

Next, notice the close correspondence between right ascension and longitude:

- Just as lines of longitude extend from the North Pole to the South Pole, lines of right ascension extend from the north celestial pole to the south celestial pole.
- Just as there is no natural starting point for longitude, there is no natural starting point for right ascension. By international treaty, longitude zero (the prime meridian) is the line of longitude that runs through Greenwich, England. By convention, right ascension zero is the line of right ascension that runs through the spring equinox.
- Longitude is measured in *degrees* east or west of Greenwich, while right ascension is measured in *hours* (and minutes and seconds) east of the spring equinox. A full 360° circle around the celestial equator goes through 24 hours of right ascension, so each hour of right ascension represents an angle of $360° \div 24 = 15°$.

As an example of how we use celestial coordinates to locate objects on the celestial sphere, consider the bright star Vega. Its coordinates are dec $= +38°44'$ and RA $= 18^{h}35^{m}$ (Figure S1.11). The positive declination tells us that Vega is 38°44′ *north* of the celestial equator. The right ascension tells us that Vega is 18 hours 35 minutes east of the spring equinox. Translating the right ascension from hours to angular degrees, we find that Vega is about 279° east of the spring equinox (because 18 hours represents $18 \times 15° = 270°$ and 35 minutes represents $\frac{35}{60} \times 15° \approx 9°$).

SEE IT FOR YOURSELF

On your plastic ball model of the celestial sphere, add a scale for right ascension along the celestial equator and also add a few circles of declination, such as declination 0°, ±30°, ±60°, and ±90°. Where is Vega on your model?

The Vega example also shows why right ascension is measured in units of time: It is because time units make it easier to track the daily motions of objects through the local sky. All objects with a particular right ascension cross the meridian at the same time, which means that all stars with RA $= 0^{h}$ cross the meridian at the same time that the spring equinox crosses the meridian. Thus, when we use time units, the right ascension of any object tells us how long *after* the spring equinox the object crosses the meridian. For example, Vega's right ascension, $18^{h}35^{m}$, tells us that on any particular day, Vega crosses the meridian about 18 hours 35 minutes after the spring equinox. (This is 18 hours 35 minutes of *sidereal time* later, which is not exactly the same as 18 hours 35 minutes of solar time; see Mathematical Insight S1.2.)

Stars are so far away that they take thousands of years or more to move noticeably on the celestial sphere. Nevertheless, the celestial coordinates of stars are not quite constant, because they are tied to the celestial equator and the celestial equator gradually moves relative to the constellations with Earth's 26,000-year cycle of axis precession [Section 2.2]. (Axis precession does not affect Earth's orbit, so it does not affect the location of the ecliptic among the constellations.) Even over just a few decades, the coordinate changes are significant enough to make a difference in precise astronomical work—such as aiming a telescope at a particular object. As a result, careful observations require almost constant updating of celestial coordinates. Star catalogs therefore always state the year for which coordinates are given (for example, "epoch 2000"). Astronomical software can automatically calculate day-to-day celestial coordinates for the Sun, Moon, and planets as they wander among the constellations.

Celestial Coordinates of the Sun Unlike stars, which remain fixed in the patterns of the constellations on the celestial sphere, the Sun moves gradually along the ecliptic. It takes a year for the Sun to make a full circuit of the ecliptic, which means it moves through all 24 hours of right ascension over the course of the year. Each month, the Sun moves approximately one-twelfth of the way around the ecliptic, meaning that its right ascension changes by about $24 \div 12 = 2$ hours per month. Figure S1.12 shows the

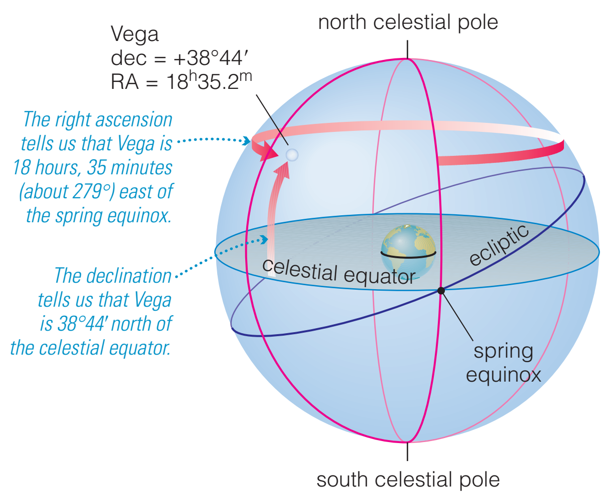


Figure S1.11 This diagram shows how we interpret the celestial coordinates of Vega.

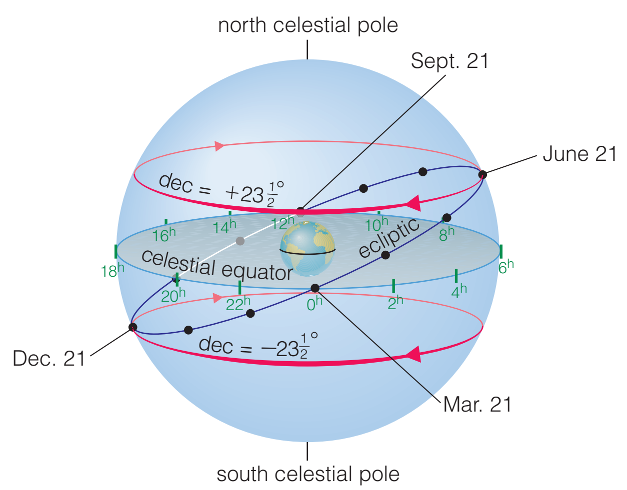


Figure S1.12 We can use this diagram of the celestial sphere to determine the Sun's right ascension and declination at monthly intervals.

ecliptic marked with the Sun's monthly position and a scale of celestial coordinates. From this figure, we can create a table of the Sun's month-by-month celestial coordinates.

Table S1.1 starts from the spring equinox, when the Sun has declination 0° and right ascension 0^h. You can see in the shaded areas of the table that while RA advances steadily through the year, the Sun's declination changes much more rapidly around the equinoxes than around the solstices. For example, the Sun's declination changes from −12° on February 21 to 12° on April 21, a difference of 24° in just 2 months. In contrast, during the 2 months around the summer solstice (that is, between May 21 and July 21), the declination varies only between +20° and its maximum of $+23\frac{1}{2}$°. This behavior explains why the number of daylight

MATHEMATICAL INSIGHT S1.2 Time by the Stars

The clocks we use in daily life are set to solar time, ticking through 24 hours for each day of mean solar time. In astronomy, it is also useful to have clocks that tell time by the stars, or **sidereal time**. Just as we define *solar time* according to the Sun's position relative to the meridian, *sidereal time* is based on the positions of stars relative to the meridian. We define the **hour angle (HA)** of any object on the celestial sphere to be the time since it last crossed the meridian. (For a circumpolar star, hour angle is measured from the *higher* of the two points at which it crosses the meridian each day.) For example:

- If a star is crossing the meridian now, its hour angle is 0^h.
- If a star crossed the meridian 3 hours ago, its hour angle is 3^h.
- If a star will cross the meridian 1 hour from now, its hour angle is -1^h or, equivalently, 23^h.

By convention, time by the stars is based on the hour angle of the spring equinox. That is, the **local sidereal time (LST)** is

$$\text{LST} = \text{HA}_{\text{spring equinox}}$$

For example, the local sidereal time is 00:00 when the spring equinox is *on* the meridian. Three hours later, when the spring equinox is 3 hours west of the meridian, the local sidereal time is 03:00.

Note that, because right ascension tells us how long after the spring equinox an object reaches the meridian, the local sidereal time is also equal to the right ascension (RA) of objects currently crossing your meridian. For example, if your local sidereal time is 04:30, stars with RA $= 4^h30^m$ are currently crossing your meridian. This idea leads to an important relationship among any object's current hour angle, the current local sidereal time, and the object's right ascension:

$$\text{HA}_{\text{object}} = \text{LST} - \text{RA}_{\text{object}}$$

This formula will make sense to you if you recognize that an object's right ascension tells us the time by which it trails the spring equinox on its daily trek through the sky. Because the local sidereal time tells us how long it has been since the spring equinox was on the meridian, the difference $\text{LST} - \text{RA}_{\text{obj}}$ must tell us the position of the object relative to the meridian.

Sidereal time has one important subtlety: Because the stars (and the celestial sphere) appear to rotate around us in one sidereal day (23^h56^m), sidereal clocks must tick through 24 hours of sidereal time in 23 hours 56 minutes of solar time. That is, a sidereal clock gains about 4 minutes per day over a solar clock. As a result, you cannot immediately infer the local sidereal time from the local solar time, or vice versa, without either doing some calculations or consulting an astronomical table. Of course, the easiest way to determine the local sidereal time is with a clock that ticks at the sidereal rate. Astronomical observatories always have sidereal clocks, and you can buy moderately priced telescopes that come with sidereal clocks.

Example 1: Suppose the local apparent solar time is 9:00 P.M. on the spring equinox (March 21). What is the local sidereal time?

Solution:

Step 1 Understand: The trick to this problem is understanding exactly what we are looking for. We are asked to find the local sidereal time, which is defined as the hour angle of the spring equinox in the local sky. Thus, we need to know where the spring equinox is located in the local sky. We are given the key clue: The date is the day of the spring equinox, the one day of the year on which the Sun is located in the same position as the spring equinox in the sky.

Step 2 Solve: We can now find the hour angle of the spring equinox from the hour angle of the Sun. We are told that the local apparent solar time is 9:00 P.M., which means that the Sun is 9 hours past the meridian and thus has an hour angle of 9 hours. Because the spring equinox and the Sun are located in the same place on this one date of the year, the hour angle of the spring equinox is also 9 hours.

Step 3 Explain: The hour angle of the spring equinox is 9 hours, which means the local sidereal time is LST = 09:00.

Example 2: Suppose the local sidereal time is LST = 04:00. When will Vega cross the meridian?

Solution:

Step 1 Understand: We are given the local sidereal time, which tells us the hour angle of the spring equinox in the local sky. To determine when Vega will cross the meridian, we need to know its hour angle, which we can calculate from its right ascension and the formula given above. Figure S1.11 shows us that Vega has RA $= 18^h35^m$, so we have all the information we need. (Appendix F also gives RA and dec for Vega and other stars.)

Step 2 Solve: We now use the formula to find Vega's hour angle from the local sidereal time and Vega's right ascension:

$$\text{HA}_{\text{Vega}} = \text{LST} - \text{RA}_{\text{Vega}} = 4{:}00 - 18{:}35 = -14{:}35$$

Step 3 Explain: Vega's hour angle is −14 hours 35 minutes, which means it will cross your meridian 14 hours and 35 minutes from now. This also means that Vega crossed your meridian 9 hours and 25 minutes ago (because $14^h35^m + 9^h25^m = 24^h$). (Note that these are intervals of sidereal time.)

Table S1.1 The Sun's Approximate Celestial Coordinates at 1-Month Intervals

Approximate Date	*RA*	*Dec*
Mar. 21 (spring equinox)	0^h	0°
Apr. 21	2^h	+12°
May 21	4^h	+20°
June 21 (summer solstice)	6^h	$+23\frac{1}{2}°$
July 21	8^h	+20°
Aug. 21	10^h	+12°
Sept. 21 (fall equinox)	12^h	0°
Oct. 21	14^h	−12°
Nov. 21	16^h	−20°
Dec. 21 (winter solstice)	18^h	$-23\frac{1}{2}°$
Jan. 21	20^h	−20°
Feb. 21	22^h	−12°

hours increases rapidly in spring and decreases rapidly in fall, while the number of daylight hours remains long and nearly constant for a couple of months around the summer solstice and short and nearly constant for a couple of months around the winter solstice.

SEE IT FOR YOURSELF

On your plastic ball model of the celestial sphere, add dots along the ecliptic to show the Sun's monthly positions. Based on your model, what are the Sun's approximate celestial coordinates on your birthday?

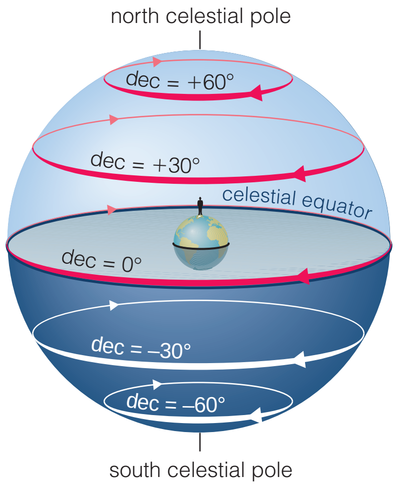
MA Seasons Tutorial, Lesson 3

How do stars move through the local sky?

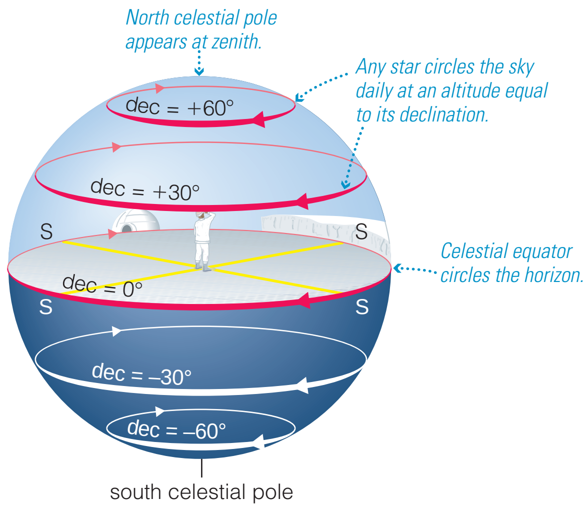
We can use our system of celestial coordinates to gain a better understanding of the way stars move through the local sky. Earth's rotation makes all celestial objects appear to circle around Earth each day (see Figure 2.9), but what we actually see in the local sky is more complex because we see only half the celestial sphere at one time (the ground blocks our view of the other half). Let's explore the appearance of the local sky. As we'll see, the path of any star through your local sky depends on only two things: (1) your latitude and (2) the declination of the star whose path you want to know.

The Sky at the North Pole The daily paths of stars are easiest to understand for the local sky at the North Pole, so let's begin there before moving on to other latitudes. Figure S1.13a shows the rotating celestial sphere and your orientation relative to it when you are standing at the North Pole. Your "up" points toward the north celestial pole, which therefore marks your zenith. Earth blocks your view of anything south of the celestial equator, which therefore runs along your horizon. To make it easier for you to visualize the local sky, Figure S1.13b shows your horizon extending to the celestial sphere. The horizon is marked with directions, but remember that all directions are south from the North Pole. We therefore cannot define a meridian for the North Pole, since a meridian would have to run from the north to the south points on the horizon and there are no such unique points at the North Pole.

Notice that the daily circles of the stars keep them at constant altitudes above or below the North Polar horizon.



a The orientation of the local sky, relative to the celestial sphere, for an observer at the North Pole.



b Extending the horizon to the celestial sphere makes it easier to visualize the local sky at the North Pole. (Note: To understand the extension, think of Earth in part (a) as being extremely small compared to the celestial sphere.)

Figure S1.13 Interactive Figure The sky at the North Pole.

Moreover, the altitude of any star is equal to its declination. For example, a star with declination +60° circles the sky at an altitude of 60°, and a star with declination −30° remains 30° below your horizon at all times. As a result, all stars north of the celestial equator are circumpolar at the North Pole, meaning that they never fall below the horizon. Stars south of the celestial equator can never be seen at the North Pole. If you are having difficulty visualizing the star paths, it may help you to watch star paths as you rotate your plastic ball model of the celestial sphere.

You should also notice that right ascension does not affect a star's path at all: The path depends only on declination. As we'll see shortly, this rule holds for all latitudes. Right ascension affects only the *time* of day and year at which a star is found in a particular position in your sky.

The Sky at the Equator After the Poles, the equatorial sky is the next easiest case to understand. Imagine that you are standing somewhere on Earth's equator (lat = 0°), such as in Ecuador, in Kenya, or on the island of Borneo. Figure S1.14a shows that "up" points directly away from (perpendicular to) Earth's rotation axis. Figure S1.14b shows the local sky more clearly by extending the horizon to the celestial sphere and rotating the diagram so the zenith is up. As everywhere except at the poles, the meridian extends from the horizon due south, through the zenith, to the horizon due north.

Look carefully at how the celestial sphere appears to rotate in the local sky. The north celestial pole remains stationary on your horizon due north. As we should expect, its altitude of 0° is equal to the equator's latitude [Section 2.1]. Similarly, the south celestial pole remains stationary on your horizon due south. At any particular time, half the celestial equator is visible, extending from the horizon due east, through the zenith, to the horizon due west. The other half lies below the horizon. As the equatorial sky appears to turn, all star paths rise straight out of the eastern horizon and set straight into the western horizon, with the following features:

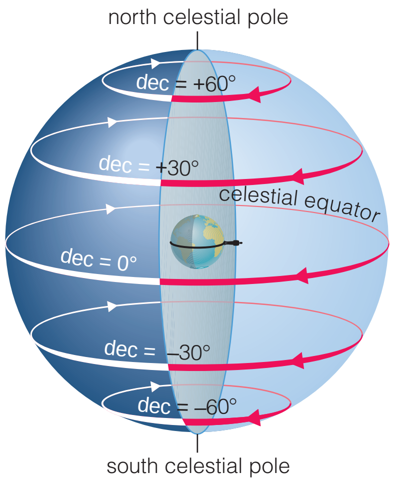
- **Stars with dec = 0°** lie *on* the celestial equator and therefore rise due east, cross the meridian at the zenith, and set due west.
- **Stars with dec > 0°** rise north of due east, reach their highest point on the meridian in the north, and set north of due west. Their rise, set, and highest point depend on their declination. For example, a star with dec = +30° rises 30° north of due east, crosses the meridian 30° to the north of the zenith—that is, at an *altitude* of 90° − 30° = 60° in the north—and sets 30° north of due west.
- **Stars with dec < 0°** rise south of due east, reach their highest point on the meridian in the south, and set south of due west. For example, a star with dec = −50° rises 50° south of due east, crosses the meridian 50° to the south of the zenith—that is, at an *altitude* of 90° − 50° = 40° in the south—and sets 50° south of due west.

Notice that exactly half of any star's daily circle lies above the horizon, which means that every star at the equator is above the horizon for exactly half of each sidereal day, or just under 12 hours, and below the horizon for the other half of the sidereal day. Also, notice again that right ascension does not affect star paths, although it does affect the time of day and year at which a star will be in a particular place along its path.

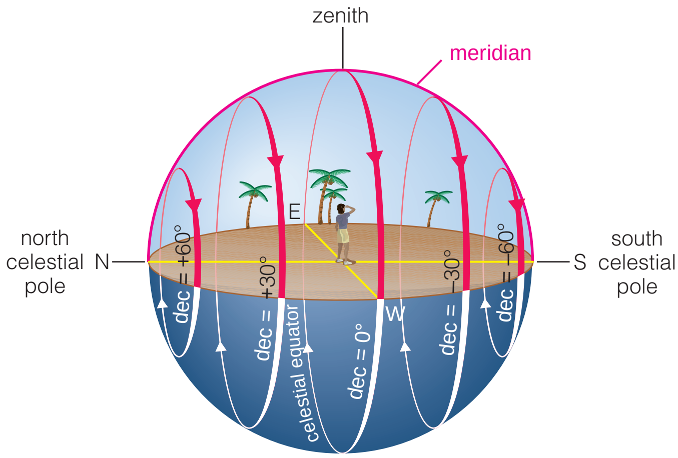
THINK ABOUT IT

Are any stars circumpolar at the equator? Are there stars that never rise above the horizon at the equator? Explain.

Skies at Other Latitudes Star tracks may at first seem more complex at other latitudes, with their mixtures of cir-



a The orientation of the local sky, relative to the celestial sphere, for an observer at Earth's equator.



b Extending the horizon and rotating the diagram make it easier to visualize the local sky at the equator.

Figure S1.14 Interactive Figure The sky at the equator.

cumpolar stars and stars that rise and set. However, they are easy to understand if we apply the same basic strategy we've used for the North Pole and equator. Let's consider latitude 40°N, such as in Denver, Indianapolis, Philadelphia, or Beijing. First, as shown in Figure S1.15a, imagine standing at this latitude on a basic diagram of the rotating celestial sphere. Note that "up" points to a location on the celestial sphere with declination +40°. To make it easier to visualize the local sky, we next extend the horizon and rotate the diagram so the zenith is up (Figure S1.15b).

As we would expect, the north celestial pole appears 40° above the horizon due north, since its altitude in the local sky is always equal to the latitude. Half the celestial equator is visible. It extends from the horizon due east, to the meridian at an altitude of 50° in the south, to the horizon due west. By comparing this diagram to that of the local sky for the equator, you can probably notice a general rule for the celestial equator at any latitude except the poles:

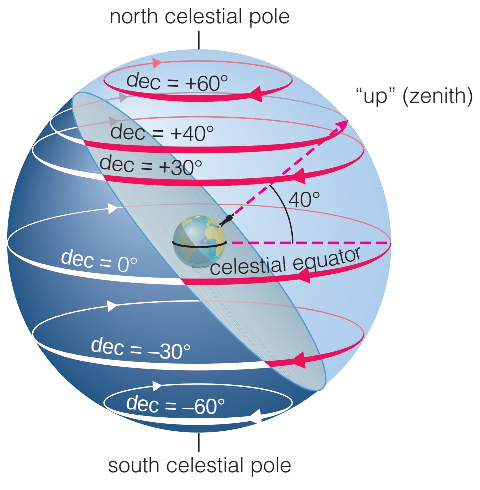
> **The celestial equator always extends from due east on your horizon to due west on your horizon, crossing the meridian at an altitude of 90° *minus* your latitude.**

The celestial equator crosses the meridian south of the zenith for locations in the Northern Hemisphere and north of the zenith for locations in the Southern Hemisphere.

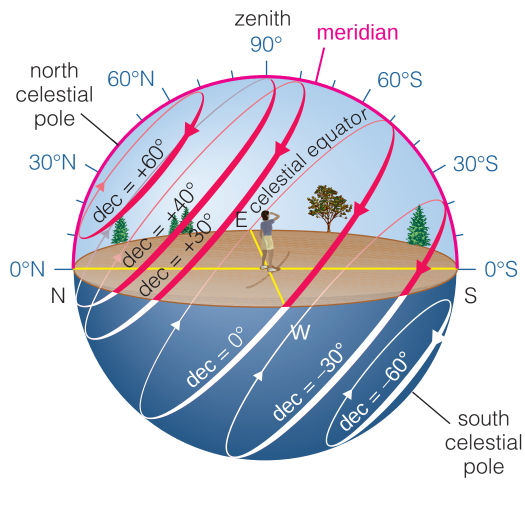
If you study Figure S1.15b carefully (or, better yet, rotate your plastic ball model of the celestial sphere with the same orientation), you'll notice the following features of the sky for latitude 40°N:

- **Stars with dec = 0°** lie *on* the celestial equator and therefore follow the path of the celestial equator through the local sky. That is, for latitude 40°N, these stars rise due east, cross the meridian at altitude 90° − 40° = 50° in the south, and set due west.
- **Stars with dec > (90° − lat)** are circumpolar. Thus, for latitude 40°N, stars with declination greater than 90° − 40° = 50° are circumpolar, because they lie *within* 40° of the north celestial pole.
- **Stars with dec > 0° but that are not circumpolar** follow paths parallel to but north of the celestial equator: They rise north of due east and set north of due west, and cross the meridian to the north of the place where the celestial equator crosses it by an amount equal to their declination. For example, because the celestial equator at latitude 40° crosses the meridian at altitude 50° in the south, a star with dec = +30° crosses the meridian at altitude 50° + 30° = 80° in the south. Similarly, a star with dec = +60° crosses the meridian 60° farther north than the celestial equator, which means at altitude 70° in the north. (To calculate this result, note that the sum 50° + 60° = 110° goes 20° past the zenith altitude of 90°, making it equivalent to 90° − 20° = 70°.)
- **Stars with dec < (−90° + lat)** never rise above the horizon. Thus, for latitude 40°N, stars with declination less than −90° + 40° = −50° never rise above the horizon, because they lie within 40° of the south celestial pole.
- **Stars with dec < 0° but that are sometimes visible** follow paths parallel to but south of the celestial equator: They rise south of due east and set south of due west, and cross the meridian south of the place where the celestial equator crosses it by an amount equal to their declination. For example, a star with dec = −30° crosses the meridian at altitude 50° − 30° = 20° in the south.

You should also notice that the fraction of any star's daily circle that is above the horizon—and hence the amount of time it is above the horizon each day—depends on its

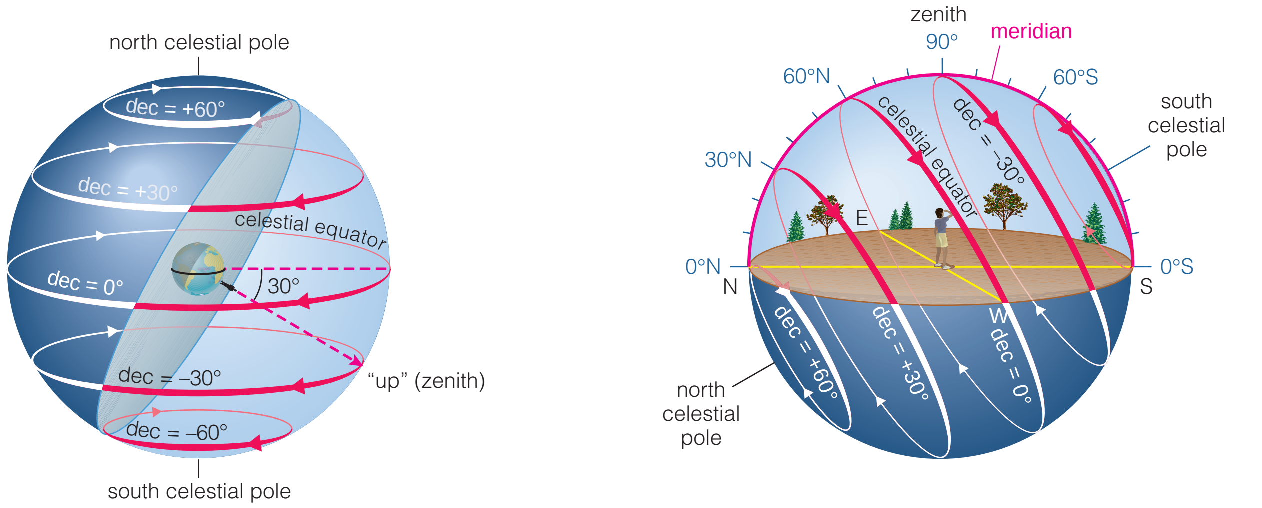


a The orientation of the local sky, relative to the celestial sphere, for an observer at latitude 40°N. Because latitude is the angle to Earth's equator, "up" points to the circle on the celestial sphere with declination +40°.



b Extending the horizon and rotating the diagram so the zenith is up make it easier to visualize the local sky. The blue scale along the meridian shows altitudes and directions in the local sky.

Figure S1.15 Interactive Figure The sky at 40°N latitude.



a The orientation of the local sky for an observer at latitude 30°S, relative to the celestial sphere. "Up" points to the circle on the celestial sphere with dec = –30°.

b Extending the horizon and rotating the diagram so the zenith is up make it easier to visualize the local sky. Note that the south celestial pole is visible at altitude 30° in the south, while the celestial equator stretches across the northern half of the sky.

Figure S1.16 Interactive Figure The sky at 30°S latitude.

declination. Because exactly half the celestial equator is above the horizon, stars on the celestial equator (dec = 0°) are above the horizon for about 12 hours per day. For northern latitudes like 40°N, stars with positive declinations have more than half their daily circles above the horizon and hence are above the horizon for more than 12 hours each day (with the range extending to 24 hours a day for the circumpolar stars). Stars with negative declinations have less than half their daily circles above the horizon and hence are above the horizon for less than 12 hours each day (with the range going to zero for stars that are never above the horizon).

We can apply the same strategy we used in Figure S1.15 to find star paths for other latitudes. Figure S1.16 shows the process for latitude 30°S. Note that the south celestial pole is visible to the south and that the celestial equator passes through the northern half of the sky. If you study the diagram carefully, you can see how star tracks depend on declination.

THINK ABOUT IT

Study Figure S1.16 for latitude 30°S. Describe the path of the celestial equator. Does it obey the 90° − lat rule given earlier? Describe how star tracks differ for stars with positive and negative declinations. What declination must a star have to be circumpolar at this latitude?

How does the Sun move through the local sky?

Like the stars and other objects on the celestial sphere, the Sun's path depends only on its declination and your latitude. However, because the Sun's declination changes over the course of the year, the Sun's path also changes.

Figure S1.17 shows the Sun's path on the equinoxes and solstices for latitude 40°N. On the equinoxes, the Sun is on the celestial equator (dec = 0°) and therefore follows the celestial equator's path: It rises due east, crosses the meridian at altitude 50° in the south, and sets due west. Like any object on the celestial equator, it is above the horizon for 12 hours. On the summer solstice, when the Sun has dec = $+23\frac{1}{2}°$ (see Table S1.1), the Sun rises well north of due east,* reaches an altitude of $50° + 23\frac{1}{2}° = 73\frac{1}{2}°$ when it crosses the meridian in the south, and sets well north of due west. The daylight hours are long because much

*Calculating exactly how far north of due east the Sun rises is beyond the scope of this book, but *SkyGazer, Starry Night,* and other astronomical software packages can tell you exactly where (and at what time) the Sun rises and sets each day.

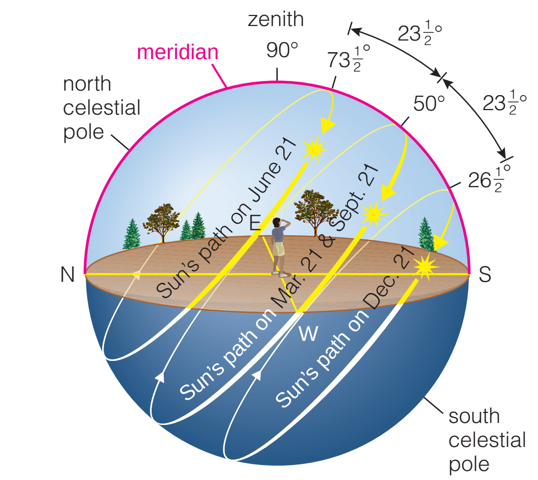


Figure S1.17 Interactive Figure The Sun's daily paths for the equinoxes and solstices at latitude 40°N.

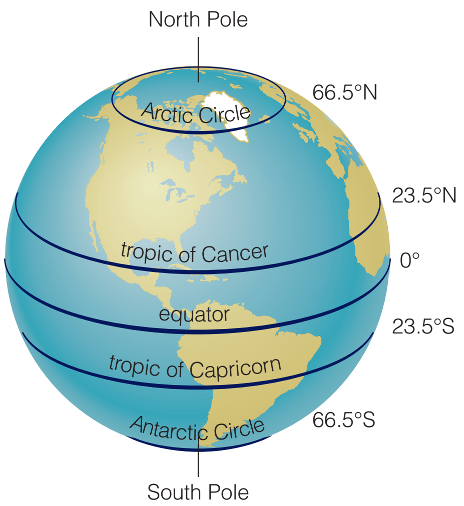


Figure S1.18 Special latitudes defined by the Sun's path through the sky.

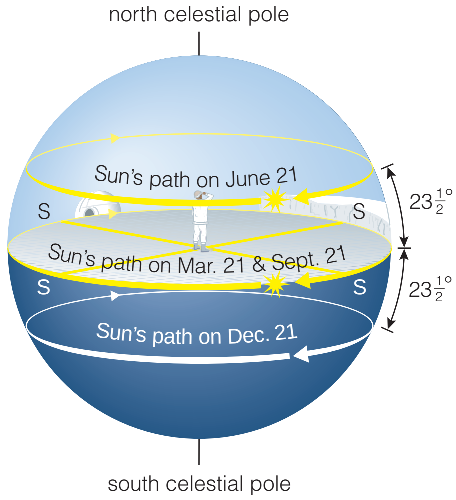


Figure S1.19 Interactive Figure Daily paths of the Sun for the equinoxes and solstices at the North Pole.

more than half the Sun's path is above the horizon. On the winter solstice, when the Sun has dec $= -23\frac{1}{2}°$, the Sun rises well south of due east, reaches an altitude of only $50° - 23\frac{1}{2}° = 26\frac{1}{2}°$ when it crosses the meridian in the south, and sets well south of due west. The daylight hours are short because much less than half the Sun's path is above the horizon.

We could make a similar diagram to show the Sun's path on various dates for any latitude. However, the $23\frac{1}{2}°$ tilt of Earth's axis makes the Sun's path particularly interesting at the special latitudes shown in Figure S1.18. Let's investigate.

The Sun at the North and South Poles Remember that the celestial equator circles the horizon at the North Pole. Figure S1.19 shows how we use this fact to find the Sun's path in the North Polar sky. Because the Sun appears *on* the celestial equator on the day of the spring equinox, the Sun circles the North Polar sky *on the horizon* on March 21, completing a full circle in 24 hours (1 solar day). Over the next 3 months, the Sun continues to circle the horizon each day, circling at gradually higher altitudes as its declination increases. It reaches its highest point on the summer solstice, when its declination of $+23\frac{1}{2}°$ means that it circles the North Polar sky at an altitude of $23\frac{1}{2}°$. After the summer solstice, the daily circles gradually fall lower over the next 3 months, reaching the horizon on the fall equinox. Then, because the Sun's declination is negative for the next 6 months (until the following spring equinox), it remains below the North Polar horizon. Thus, the North Pole essentially has 6 months of daylight and 6 months of darkness, with an extended twilight that lasts a few weeks beyond the fall equinox and an extended dawn that begins a few weeks before the spring equinox.

The situation is the opposite at the South Pole. Here the Sun's daily circle first reaches the horizon on the fall equinox. The daily circles then rise gradually higher, reaching a maximum altitude of $23\frac{1}{2}°$ on the *winter* solstice, and then slowly fall back to the horizon on the spring equinox. Thus, the South Pole has the Sun above the horizon during the 6 months it is below the north polar horizon.

Although we've correctly described the Sun's true position in the polar skies over the course of the year, two effects complicate what we actually see at the poles around the times of the equinoxes. First, the atmosphere bends light enough so that the Sun *appears* to be slightly above the horizon even when it is actually slightly below it. Near the horizon, this bending makes the Sun appear about 1° higher than it would in the absence of an atmosphere. Second, the Sun's angular size of about $\frac{1}{2}°$ means that it does not fall below the horizon at a single moment but instead sets gradually. Together, these effects mean that the Sun appears above each polar horizon for slightly longer (by several days) than 6 months each year.

The Sun at the Equator At the equator, the celestial equator extends from the horizon due east, through the zenith, to the horizon due west. The Sun therefore follows this path on each equinox, reaching the zenith at local noon (Figure S1.20). Following the spring equinox, the Sun's increasing declination means that it follows a daily track that takes it gradually northward in the sky. It is farthest north on the summer solstice, when it rises $23\frac{1}{2}°$ north of due east, crosses the meridian at altitude $90° - 23\frac{1}{2}° = 66\frac{1}{2}°$ in the north, and sets $23\frac{1}{2}°$ north of due west. Over the next 6 months, it gradually tracks southward until the winter solstice, when its path is the mirror image (across the celestial equator) of its summer solstice path.

Like all objects in the equatorial sky, the Sun is always above the horizon for half a day and below it for half a day. Moreover, the Sun's track is highest in the sky on the equinoxes and lowest on the summer and winter solstices. That is why equatorial regions do not have four seasons like temperate regions [Section 2.2]. The Sun's path in the equatorial sky also makes it rise and set perpendicular to the horizon every day of the year, making for a more rapid dawn and a briefer twilight than at other latitudes.

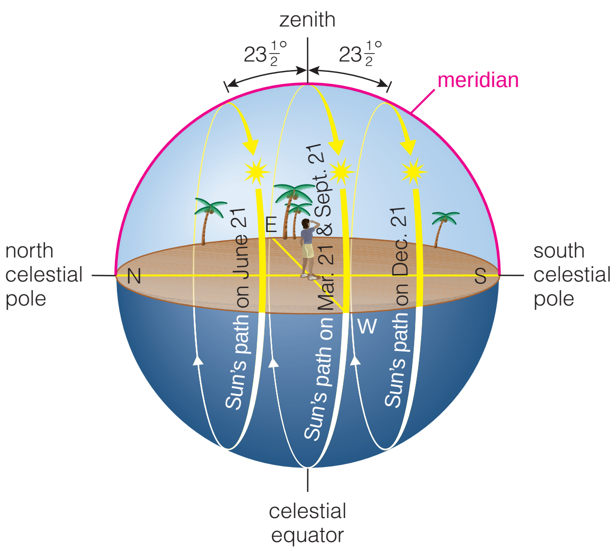


Figure S1.20 Interactive Figure Daily paths of the Sun for the equinoxes and solstices at the equator.

The Sun at the Tropics The circles of latitude 23.5°N and 23.5°S are called the **tropic of Cancer** and the **tropic of Capricorn**, respectively (see Figure S1.18). The region between these two circles, generally called the *tropics*, represents the parts of Earth where the Sun can sometimes reach the zenith at noon.

Figure S1.21 shows why the tropic of Cancer is special. The celestial equator extends from due east on the horizon to due west on the horizon, crossing the meridian in the south at an altitude of $90° - 23\frac{1}{2}°$(the latitude) $= 66\frac{1}{2}°$. The Sun follows this path on the equinoxes (March 21 and September 21). As a result, the Sun's path on the summer solstice, when it crosses the meridian $23\frac{1}{2}°$ northward of the celestial equator, takes it to the zenith at local noon. Because the Sun has its maximum declination on the summer solstice, the tropic of Cancer marks the northernmost latitude at which the Sun ever reaches the zenith. Similarly, at the tropic of Capricorn the Sun reaches the zenith at local noon on the winter solstice, making this the southernmost latitude at which the Sun ever reaches the zenith. Between the two tropic circles, the Sun passes through the zenith twice a year; the precise dates vary with latitude.

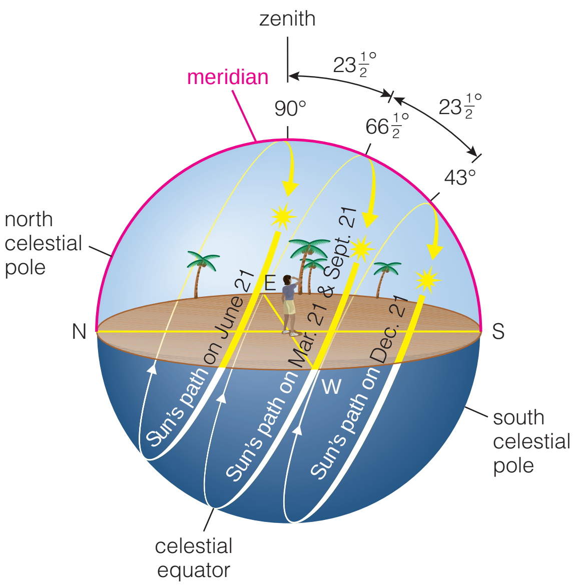


Figure S1.21 Interactive Figure Daily paths of the Sun for the equinoxes and solstices at the tropic of Cancer.

The Sun at the Arctic and Antarctic Circles At the equator, the Sun is above the horizon for 12 hours each day year-round. At latitudes progressively farther from the equator, the daily time that the Sun is above the horizon varies progressively more with the seasons. The special latitudes at which the Sun remains continuously above the horizon for a full day each year are the polar circles: the **Arctic Circle** at latitude 66.5°N and the **Antarctic Circle** at latitude 66.5°S (see Figure S1.18). Poleward of these circles, the length of continuous daylight (or darkness) increases beyond 24 hours, reaching the extreme of 6 months at the North and South Poles.

Figure S1.22 shows why the Arctic Circle is special. The celestial equator extends from due east on the horizon to due west on the horizon, crossing the meridian in the south at an altitude of $90° - 66\frac{1}{2}°$(the latitude) $= 23\frac{1}{2}°$. As a result, the Sun's path is circumpolar on the summer solstice: It skims the northern horizon at midnight, rises through the eastern sky to a noon maximum altitude of 47° in the south (which is the celestial equator's maximum altitude of $23\frac{1}{2}°$ plus the Sun's summer solstice declination of $23\frac{1}{2}°$), and then gradually falls through the western sky until it is back on the horizon at midnight (see the photograph of this path in Figure 2.18). At the Antarctic Circle, the Sun follows the same basic pattern on the winter solstice, except that it skims the horizon in the south and rises to a noon maximum altitude of 47° in the north.

However, as at the North and South Poles, what we actually see at the polar circles is slightly different from this idealization. Again, the bending of light by Earth's atmosphere and the Sun's angular size of about $\frac{1}{2}°$ make the

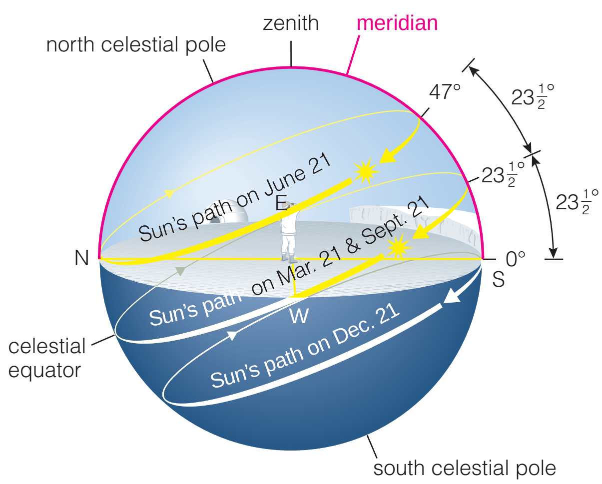


Figure S1.22 Interactive Figure Daily paths of the Sun for the equinoxes and solstices at the Arctic Circle.

Sun *appear* to be slightly above the horizon even when it is slightly below it. Thus, the Sun seems not to set for several days, rather than for a single day, around the summer solstice at the Arctic Circle (the winter solstice at the Antarctic Circle). Similarly, the Sun appears to peek above the horizon momentarily, rather than not at all, around the winter solstice at the Arctic Circle (the summer solstice at the Antarctic Circle).

S1.3 Principles of Celestial Navigation

We now have all the background we need to cover the basic principles of celestial navigation. Imagine that you're on a ship at sea, far from any landmarks. How can you figure out where you are? It's easy if you understand the apparent motions of the sky that we have already discussed in this chapter.

How can you determine your latitude?

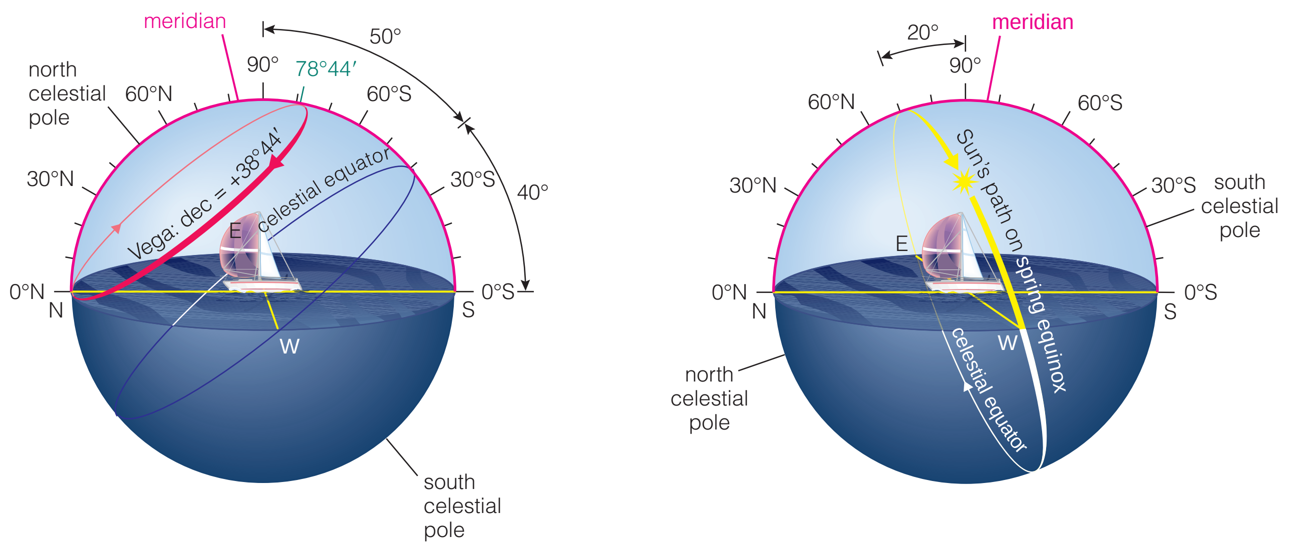
Determining latitude is particularly easy if you can find the north or south celestial pole: Your latitude is equal to the altitude of the celestial pole in your sky. In the Northern Hemisphere at night, you can determine your approximate latitude by measuring the altitude of Polaris. Because Polaris has a declination within 1° of the north celestial pole, its altitude is within 1° of your latitude. For example, if Polaris has altitude 17°, your latitude is between 16°N and 18°N.

If you want to be more precise, you can determine your latitude from the altitude of *any* star as it crosses your meridian. For example, suppose Vega happens to be crossing your meridian right now and it appears in your southern sky at altitude 78°44′. Because Vega has dec = +38°44′ (see Figure S1.11), it crosses your meridian 38°44′ north of the celestial equator. As shown in Figure S1.23a, you can conclude that the celestial equator crosses your meridian at an altitude of precisely 40° in the south. Your latitude must therefore be 50°N because the celestial equator always crosses the meridian at an altitude of 90° minus the latitude. You know you are in the Northern Hemisphere because the celestial equator crosses the meridian in the south.

In the daytime, you can find your latitude from the Sun's altitude on your meridian if you know the date and have a table that tells you the Sun's declination on that date. For example, suppose the date is March 21 and the Sun crosses your meridian at altitude 70° in the north (Figure S1.23b). Because the Sun has dec = 0° on March 21, you can conclude that the celestial equator also crosses your meridian in the north at altitude 70°. You must be in the Southern Hemisphere, because the celestial equator crosses the meridian in the north. From the rule that the celestial equator crosses the meridian at an altitude of 90° minus the latitude, you can conclude that you are at latitude 20°S.

How can you determine your longitude?

You can determine your longitude by comparing the current position of an object in your sky with its position as seen from some known longitude. As a simple example,



a Because Vega has dec = +38°44', it crosses the meridian 38°44' north of the celestial equator. Because Vega crosses the meridian at altitude 78°44' in the south, the celestial equator must cross the meridian at altitude 40° in the south. Thus, the latitude must be 50°N.

b To determine latitude from the Sun's meridian crossing, you must know the Sun's declination, which you can determine from the date. The case shown is for the spring equinox, when the Sun's declination is 0° and hence follows the path of the celestial equator through the local sky. Because the celestial equator crosses the meridian at 70° in the north, the latitude must be 20°S.

Figure S1.23 Determining latitude from a star and from the Sun.

suppose you use a sundial to determine that the apparent solar time is 1:00 P.M., which means the Sun passed the meridian 1 hour ago. You immediately call a friend in England and learn that it is 3:00 P.M. in Greenwich (or you carry a clock that keeps Greenwich time). You now know that your local time is 2 hours earlier than the local time in Greenwich, which means you are 2 hours west of Greenwich. (An earlier time means that you are *west* of Greenwich, because Earth rotates from west to east.) Each hour corresponds to 15° of longitude, so "2 hours west of Greenwich" means longitude 30°W.

At night, you can find your longitude by comparing the positions of stars in your local sky and at some known longitude. For example, suppose Vega is on your meridian and a call to your friend reveals that it won't cross the meridian in Greenwich until 6 hours from now. In this case, your local time is 6 hours later than the local time in Greenwich. Thus, you are 6 hours east of Greenwich, or at longitude 90°E (because $6 \times 15° = 90°$).

Celestial Navigation in Practice Although celestial navigation is easy in principle, at least three considerations make it more difficult in practice. First, finding either latitude or longitude requires a tool for measuring angles in the sky. One such device, called an *astrolabe,* was invented by the ancient Greeks and significantly improved by Islamic scholars during the Middle Ages. The astrolabe's faceplate (Figure S1.24a) could be used to tell time, because it consisted of a rotating star map and horizon plates for specific latitudes. Today you can buy similar rotatable star maps, called *planispheres.* Most astrolabes contained a sighting stick on the back that allowed users to measure the altitudes of bright stars in the sky. These measurements could then be correlated against special markings under the faceplate (Figure S1.24b). Astrolabes were effective but difficult and expensive to make. As a result, medieval sailors often measured angles with a simple pair of calibrated perpendicular sticks, called a *cross-staff* or *Jacob's staff* (Figure S1.24c). A more modern device called a *sextant* allows much more precise angle determinations by incorporating a small telescope for sightings (Figure S1.24d). Sextants are still used for celestial navigation on many ships. If you want to practice celestial navigation yourself, you can buy an inexpensive plastic sextant at many science-oriented stores.

Figure S1.24 Navigational instruments.

a The faceplate of an astrolabe; many astrolabes had sighting sticks on the back for measuring positions of bright stars.

b A copper engraving of Italian explorer Amerigo Vespucci (for whom America was named) using an astrolabe to sight the Southern Cross. The engraving by Philip Galle, from the book *Nova Reperta*, was based on an original by Joannes Stradanus in the early 1580s.

c A woodcutting of Ptolemy holding a cross-staff (artist unknown).

d A sextant.

A second practical consideration is knowing the celestial coordinates of stars and the Sun so that you can determine their paths through the local sky. At night, you can use a table listing the celestial coordinates of bright stars. In addition to knowing the celestial coordinates, you must either know the constellations and bright stars extremely well or carry star charts to help you identify them. For navigating by the Sun in the daytime, you'll need a table listing the Sun's celestial coordinates on each day of the year.

The third practical consideration applies to determining longitude: You need to know the current position of the Sun (or a particular star) in a known location, such as Greenwich, England. Although you could determine this by calling a friend who lives there, it's more practical to carry a clock set to universal time (that is, Greenwich mean time). In the daytime, the clock makes it easy to determine your longitude. If apparent solar time is 1:00 P.M. in your location and the clock tells you that it is 3:00 P.M. in Greenwich, then you are 2 hours west of Greenwich, or at longitude 30°W. The task is more difficult at night, because you must compare the position of a *star* in your sky to its current position in Greenwich. You can do this with the aid of detailed astronomical tables that allow you to determine the current position of any star in the Greenwich sky from the date and the universal time.

Historically, this third consideration created enormous problems for navigation. Before the invention of accurate clocks, sailors could easily determine their latitude but not their longitude. Indeed, most of the European voyages of discovery beginning in the 1400s relied on little more than guesswork about longitude, although some sailors learned complex mathematical techniques for estimating longitude through observations of the lunar phases. More accurate longitude determination, upon which the development of extensive ocean commerce and travel depended, required the invention of a clock that would remain accurate on a ship rocking in the ocean swells. By the early 1700s, solving this problem was considered so important that the British government offered a substantial monetary prize for the solution. John Harrison claimed the prize in 1761, with a clock that lost only 5 seconds during a 9-week voyage to Jamaica.*

The Global Positioning System In the past couple of decades, a new type of celestial navigation has supplanted traditional methods. It finds positions relative to a set of satellites in Earth orbit. These satellites of the **global positioning system (GPS)** in essence function like artificial stars. The satellites' positions at any moment are known precisely from their orbital characteristics. The GPS currently uses about two dozen satellites orbiting Earth at an altitude of 20,000 kilometers. Each satellite transmits a radio signal that a small radio receiver can pick up—rain or shine, day or night. Each GPS receiver has a built-in computer that calculates your precise position on Earth by comparing the signals received from several GPS satellites.

The United States originally built the GPS in the late 1970s for military use. Today, the many applications of the GPS include automobile navigation systems as well as systems for helping airplanes land safely, guiding the blind around town, and helping lost hikers find their way. Geologists have used the GPS to measure *millimeter*-scale changes in Earth's crust.

With rapid growth in the use of GPS navigation, the ancient practice of celestial navigation is in danger of becoming a lost art. Fortunately, many amateur clubs and societies are keeping the skills of celestial navigation alive.

*The story of the difficulties surrounding the measurement of longitude at sea and how Harrison finally solved the problem is chronicled in *Longitude*, by Dava Sobel (Walker and Company, 1995).

COMMON MISCONCEPTIONS

Compass Directions

Most people determine direction with the aid of a compass rather than the stars. However, a compass needle doesn't actually point to true geographic north. Instead, the compass needle responds to Earth's magnetic field and points to *magnetic* north, which can be substantially different from true north. If you want to navigate precisely with a compass, you need a special map that takes into account local variations in Earth's magnetic field. Such maps are available at most camping stores. They are not perfectly reliable, however, because the magnetic field also varies with time. In general, celestial navigation is much more reliable for determining direction than using a compass.

THE BIG PICTURE

Putting Chapter S1 into Context

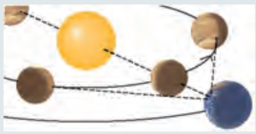
In this chapter, we built upon concepts from the first three chapters to form a more detailed understanding of celestial timekeeping and navigation. We also learned how to determine paths for the Sun and the stars in the local sky. As you look back at what you've learned, keep in mind the following "big picture" ideas:

- Our modern systems of timekeeping are rooted in the apparent motions of the Sun through the sky. Although it's easy to forget these roots when you look at a clock or a calendar, the sky was the only guide to time for most of human history.
- The term *celestial navigation* sounds a bit mysterious, but it refers to simple principles that allow you to determine your location on Earth. Even if you're never lost at sea, you may find the basic techniques of celestial navigation useful to orient yourself at night (for example, on your next camping trip).
- If you understand the apparent motions of the sky discussed in this chapter and also learn the constellations and bright stars, you'll feel very much "at home" under the stars at night.

SUMMARY OF KEY CONCEPTS

S1.1 Astronomical Time Periods

- **How do we define the day, month, year, and planetary periods?** Each of these is defined in two ways. A **sidereal day** is Earth's rotation period, which is about 4 minutes shorter than the 24-hour **solar day** from noon one day to noon the next day. A **sidereal month** is the Moon's orbital period of about $27\frac{1}{3}$ days; a **synodic month** is the $29\frac{1}{2}$ days required for the Moon's cycle of phases. A **sidereal year** is Earth's orbital period, which is about 20 minutes longer than the **tropical year** from one spring equinox to the next. A planet's **sidereal period** is its orbital period, and its **synodic period** is the time from one opposition or conjunction to the next.

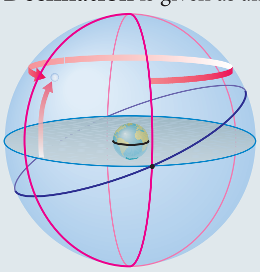


- **How do we tell the time of day?** There are several time measurement systems. **Apparent solar time** is based on the Sun's position in the local sky. **Mean solar time** is also local, but it averages the changes in the Sun's rate of motion over the year. **Standard time** and **daylight saving time** divide the world into time zones. **Universal time** is the mean solar time in Greenwich, England.

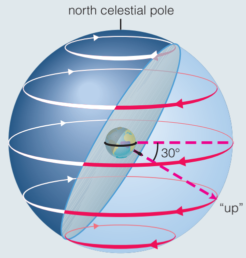
- **When and why do we have leap years?** We usually have a **leap year** every 4 years because the length of the year is $365\frac{1}{4}$ days. However, it is not exactly $365\frac{1}{4}$ days, so our calendar skips a leap year in century years not divisible by 400.

S1.2 Celestial Coordinates and Motion in the Sky

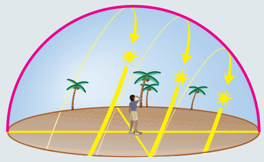
- **How do we locate objects on the celestial sphere?** **Declination** is given as an angle describing an object's position north or south of the celestial equator. **Right ascension**, usually measured in hours (and minutes and seconds), tells us how far east an object is located relative to the spring equinox.



- **How do stars move through the local sky?** A star's path through the local sky depends on its declination and your latitude. Latitude tells you the orientation of your sky relative to the celestial sphere, while declination tells you how a particular star's path compares to the path of the celestial equator through your sky.

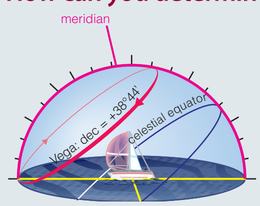


- **How does the Sun move through the local sky?** The Sun's path also depends on its declination and your latitude, but it varies throughout the year because its declination varies. The Sun's varying path helps define special latitudes, including the **tropics of Cancer** and **Capricorn** and the **Arctic** and **Antarctic Circles**.



S1.3 Principles of Celestial Navigation

- **How can you determine your latitude?** You can determine your latitude from the altitude of the celestial pole in your sky or by measuring the altitude and knowing the declination of a star (or the Sun) as it crosses your meridian.



- **How can you determine your longitude?** To determine longitude you must know the position of the Sun or a star in your sky and its position at the same time in the sky of Greenwich, England (or some other specific location). This is most easily done if you have a clock that tells universal time.

EXERCISES AND PROBLEMS

For instructor-assigned homework go to **www.masteringastronomy.com.**

MasteringASTRONOMY

Review Questions

Short-Answer Questions Based on the Reading

1. Why is a *sidereal day* shorter than a *solar day*?
2. What is the difference between a *sidereal month* and a *synodic month*? Between a *sidereal year* and a *tropical year*? Between a planet's *sidereal period* and its *synodic period*?
3. What do we mean by *opposition, conjunction*, and *greatest elongation* for planets? Explain both for planets closer than Earth to the Sun and for planets farther than Earth from the Sun.
4. Under what circumstances do we see a *transit* of a planet across the Sun?
5. What is *apparent solar time*? Why is it different from *mean solar time*? How are *standard time, daylight saving time*, and *universal time* related to mean solar time?
6. Describe the origins of the Julian and Gregorian calendars. Which one do we use today?

7. What do we mean when we say the equinoxes and solstices are points on the celestial sphere? How are these points related to the times of year called the equinoxes and solstices?
8. What are *declination* and *right ascension*? How are these celestial coordinates similar to latitude and longitude on Earth? How are they different?
9. How and why do the Sun's celestial coordinates change over the course of each year?
10. Suppose you are standing at the North Pole. Where is the celestial equator in your sky? Where is the north celestial pole? Describe the daily motion of the sky. Do the same for the sky at the equator and at latitude 40°N.
11. Describe the Sun's paths through the local sky on the equinoxes and on the solstices for latitude 40°N. Do the same for the North Pole, South Pole, and equator.
12. What is special about the tropics of Cancer and Capricorn? Describe the Sun's path on the solstices at these latitudes. Do the same for the Arctic and Antarctic Circles.
13. Briefly describe how you can use the Sun or stars to determine your latitude and longitude.
14. What is the global positioning system (GPS)?

Test Your Understanding

Does It Make Sense?

Decide whether the statement makes sense (or is clearly true) or does not make sense (or is clearly false). Explain clearly; not all of these have definitive answers, so your explanation is more important than your chosen answer.

(*Hint:* For statements that involve coordinates—such as altitude, longitude, or declination—check whether the correct coordinates are used for the situation. For example, it does not make sense to describe a location on Earth by an altitude since altitude makes sense only for positions of objects in the local sky.)

15. Last night I saw Venus shining brightly on the meridian at midnight.
16. The apparent solar time was noon, but the Sun was just setting.
17. My mean solar clock said it was 2:00 P.M., but a friend who lives east of here had a mean solar clock that said it was 2:11 P.M.
18. When the standard time is 3:00 P.M. in Baltimore, it is 3:15 P.M. in Washington, D.C.
19. Last night around 8:00 P.M. I saw Jupiter at an altitude of 45° in the south.
20. The latitude of the stars in Orion's belt is about 5°N.
21. Today the Sun is at an altitude of 10° on the celestial sphere.
22. Los Angeles is west of New York by about 3 hours of right ascension.
23. The summer solstice is east of the vernal equinox by 6 hours of right ascension.
24. Even though my UT clock had stopped, I was able to find my longitude by measuring the altitudes of 14 different stars in my local sky.

Quick Quiz

Choose the best answer to each of the following. Explain your reasoning with one or more complete sentences.

25. The time from one spring equinox to the next is the (a) sidereal day. (b) tropical year. (c) synodic month.
26. Jupiter is brightest when it is (a) at opposition. (b) at conjunction. (c) closest to the Sun in its orbit.
27. Venus is easiest to see in the evening when it is (a) at superior conjunction. (b) at inferior conjunction. (c) at greatest eastern elongation.
28. In the winter, your wristwatch tells (a) apparent solar time. (b) standard time. (c) universal time.
29. A star that is located 30° north of the celestial equator has (a) declination = 30°. (b) right ascension = 30°. (c) latitude = 30°.
30. A star's path through your sky depends on your latitude and the star's (a) declination. (b) right ascension. (c) both declination and right ascension.
31. At latitude 50°N, the celestial equator crosses the meridian at altitude (a) 50° in the south. (b) 50° in the north.(c) 40° in the south.
32. At the North Pole on the summer solstice, the Sun (a) remains stationary in the sky. (b) reaches the zenith at noon. (c) circles the horizon at altitude $23\frac{1}{2}$°.
33. If you know a star's declination, you can determine your latitude if you also (a) measure its altitude when it crosses the meridian. (b) measure its right ascension. (c) know the universal time.
34. If you measure the Sun's position in your local sky, you can determine your longitude if you also (a) measure its altitude when it crosses the meridian. (b) know its right ascension and declination. (c) know the universal time.

Process of Science

Examining How Science Works

35. *Transits and the Geocentric Universe.* Ancient people could not observe transits of Mercury or Venus across the Sun, because they lacked instruments for viewing a small dark spot against the Sun. But suppose they could have seen a transit. Would this observation have provided evidence against the Earth-centered universe? If so, explain why. If not, can you think of any related observations that qualify as evidence against the geocentric view? (Hint: See Figure 3.24.)
36. *Geometry and Science.* As discussed in Mathematical Insight S1.1, Copernicus found that a Sun-centered model led him to a simple geometric layout for the solar system, a fact that gave him confidence that his model was on the right track. Did the mathematics actually prove that the Sun-centered model was correct, or was it just one step in the longer process of the Copernican revolution? Use your answer to briefly discuss the role of mathematics in science.
37. *Daylight Saving Time.* Find out why Congress decided to extend the period of daylight saving time by four additional weeks, starting in 2007. Do you think this change was based on science? Defend your opinion.

Investigate Further

In-Depth Questions to Increase Your Understanding

Short-Answer/Essay Questions

38. *Opposite Rotation.* Suppose Earth rotated in a direction opposite to its orbital direction; that is, suppose it rotated clockwise (as seen from above the North Pole) but orbited counterclockwise. Would the solar day still be longer than the sidereal day? Explain.
39. *No Precession.* Suppose Earth's axis did *not* precess. Would the sidereal year still be different from the tropical year? Explain.

40. *Fundamentals of Your Local Sky.* Answer each of the following for *your* latitude.
    a. Where is the north (or south) celestial pole in your sky?
    b. Describe the location of the meridian in your sky. Specify its shape and at least three distinct points along it (such as the points at which it meets your horizon and its highest point).
    c. Describe the location of the celestial equator in your sky. Specify its shape and at least three distinct points along it (such as the points at which it meets your horizon and crosses your meridian).
    d. Does the Sun ever appear at your zenith? If so, when? If not, why not?
    e. What range of declinations makes a star circumpolar in your sky? Explain.
    f. What is the range of declinations for stars that you can never see in your sky? Explain.
41. *Sydney Sky.* Repeat Problem 40 for the local sky in Sydney, Australia (latitude 34°S).
42. *Path of the Sun in Your Sky.* Describe the path of the Sun through your local sky for each of the following days.
    a. The spring and fall equinoxes.
    b. The summer solstice.
    c. The winter solstice.
    d. Today. (*Hint:* Estimate the right ascension and declination of the Sun for today's date by using the data in Table S1.1).
43. *Sydney Sun.* Repeat Problem 42 for the local sky in Sydney, Australia (latitude 34°S).
44. *Lost at Sea I.* During an upcoming vacation, you decide to take a solo boat trip. While contemplating the universe, you lose track of your location. Fortunately, you have some astronomical tables and instruments, as well as a UT clock. You thereby put together the following description of your situation:
    - It is the spring equinox.
    - The Sun is on your meridian at altitude 75° in the south.
    - The UT clock reads 22:00.
    a. What is your latitude? How do you know?
    b. What is your longitude? How do you know?
    c. Consult a map. Based on your position, where is the nearest land? Which way should you sail to reach it?
45. *Lost at Sea II.* Repeat Problem 44, based on the following description of your situation:
    - It is the day of the summer solstice.
    - The Sun is on your meridian at altitude $67\frac{1}{2}°$ in the north.
    - The UT clock reads 06:00.
46. *Lost at Sea III.* Repeat Problem 44, based on the following description of your situation:
    - Your local time is midnight.
    - Polaris appears at altitude 67° in the north.
    - The UT clock reads 01:00.
47. *Lost at Sea IV.* Repeat Problem 44, based on the following description of your situation:
    - Your local time is 6 A.M.
    - From the position of the Southern Cross, you estimate that the south celestial pole is at altitude 33° in the south.
    - The UT clock reads 11:00.
48. *The Sun from Mars.* Mars has an axis tilt of 25.2°, only slightly larger than that of Earth. Compared to Earth, is the range of latitudes on Mars for which the Sun can reach the zenith larger or smaller? Is the range of latitudes for which the Sun is circumpolar larger or smaller? Make a sketch of Mars similar to the one for Earth in Figure S1.18.

Quantitative Problems

Be sure to show all calculations clearly and state your final answers in complete sentences.

49. *Solar and Sidereal Days.* Suppose Earth orbited the Sun in 6 months rather than 1 year but had the same rotation period. How much longer would a solar day be than a sidereal day? Explain.
50. *Saturn's Orbital Period.* Saturn's synodic period is 378.1 days. What is its actual orbital period?
51. *Mercury's Orbital Period.* Mercury's synodic period is 115.9 days. What is its actual orbital period?
52. *New Asteroid.* You discover an asteroid with a synodic period of 429 days. What is its actual orbital period?
53. *Using the Analemma I.* It's February 15 and your sundial tells you the apparent solar time is 18 minutes until noon. What is the mean solar time?
54. *Using the Analemma II.* It's July 1 and your sundial tells you that the apparent solar time is 3:30 P.M. What is the mean solar time?
55. *Find the Sidereal Time.* It is 4 P.M. on the spring equinox. What is the local sidereal time?
56. *Where's Vega?* The local sidereal time is 19:30. When will Vega cross your meridian?
57. *Find Right Ascension.* You observe a star that has an hour angle of 13 hours (13^h) when the local sidereal time is 8:15. What is the star's right ascension?
58. *Where's Orion?* The Orion Nebula has declination of about $-5.5°$ and right ascension of 5^h25^m. If you are at latitude 40°N and the local sidereal time is 7:00, approximately where does the Orion Nebula appear in your sky?
59. *Meridian Crossings of the Moon and Phobos.* Estimate the time between meridian crossings of the Moon for a person standing on Earth. Repeat your calculation for meridian crossings of the Martian moon Phobos. Use the Appendices in the back of the book if necessary.
60. *Mercury's Rotation Period.* Mercury's sidereal day is approximately $\frac{2}{3}$ of its orbital period, or about 58.6 days. Estimate the length of Mercury's solar day. Compare to Mercury's orbital period of about 88 days.

Discussion Questions

61. *Northern Chauvinism.* Why is the solstice in June called the *summer solstice,* when it marks winter for places like Australia, New Zealand, and South Africa? Why is the writing on maps and globes usually oriented so that the Northern Hemisphere is at the top, even though there is no up or down in space? Discuss.
62. *Celestial Navigation.* Briefly discuss how you think the benefits and problems of celestial navigation might have affected ancient sailors. For example, how did they benefit from using the north celestial pole to tell directions, and what problems did they experience because of the difficulty in determining longitude? Can you explain why ancient sailors generally hugged coastlines as much as possible on their voyages? What dangers did this type of sailing pose? Why did the Polynesians become the best navigators of their time?

MEDIA EXPLORATIONS

For self-study activities go to **www.masteringastronomy.com.**

Mastering ASTRONOMY

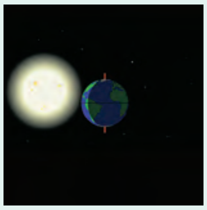
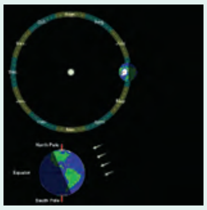
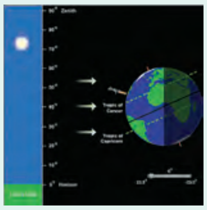
Interactive Tutorials

Tutorial Review of Key Concepts

Use the interactive **Tutorials** at **www.masteringastronomy.com** to review key concepts from this chapter.

Seasons Tutorial

Lesson 2 The Solstices and Equinoxes
Lesson 3 The Sun's Position in the Sky

Supplementary Tutorial Exercises

Use the interactive **Tutorial Lessons** to explore the following questions.

Seasons Tutorial, Lesson 2

1. How are the solstices and equinoxes related to Earth's orbital position around the Sun?
2. What are day and night like at the North Pole?
3. How does the length of the day vary with the seasons at the Antarctic Circle?

Seasons Tutorial, Lesson 3

1. When can you see the Sun directly over the equator?
2. Where can you see the Sun directly overhead on the winter solstice?
3. When is the Sun seen directly overhead at your latitude?

Exploring the Sky and Solar System

Of the many activities available on the ***Voyager: SkyGazer*** **CD-ROM** accompanying your book, use the following files to observe key phenomena covered in this chapter.

Go to the **File: Basics** folder for the following demonstrations.

1. Analemma
2. Rubber Horizon
3. Three Cities

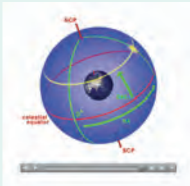
Go to the **File: Demo** folder for the following demonstrations.

1. Venus Transit of 1769
2. Celestial Poles
3. Russian Midnight Sun

Movies

Check out the following narrated and animated short documentaries available on **www.masteringastronomy.com** for a helpful review of key ideas covered in this chapter.

Time and Seasons Movie



The Celestial Sphere Movie

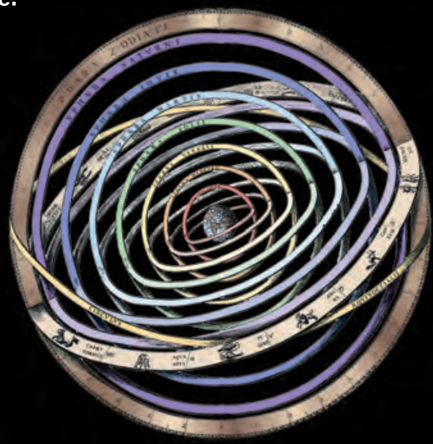
Web Projects

1. *Sundials.* Although they are no longer necessary for timekeeping, sundials remain popular for their cultural and artistic value. Search the Web for pictures and information about interesting sundials around the world. Write a short report about at least three sundials that you find particularly interesting.
2. *The Analemma.* Learn more about the analemma and its uses from information available on the Web. Write a short report on your findings.
3. *Calendar History.* Investigate the history of the Julian or Gregorian calendar in greater detail. Write a short summary of some interesting aspect of the history you learn from your Web research. (For example, why did Julius Caesar allow one year to have 445 days? How did our months end up with 28, 30, or 31 days?)
4. *Global Positioning System.* Learn more about the global positioning system and its uses. Write a short report summarizing how you think the growing availability of GPS will affect our lives over the next 10 years.

COSMIC CONTEXT PART I Our Expanding Perspective

Our perspective on the universe has changed dramatically throughout human history. This timeline summarizes some of the key discoveries that have shaped our modern perspective.

Stonehenge



Earth-centered model of the universe

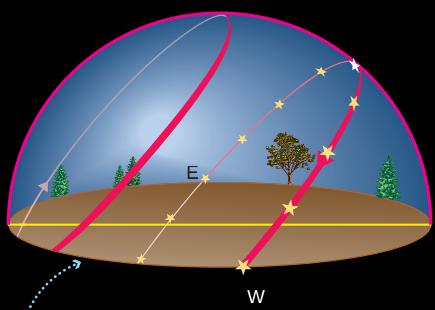
Galileo's telescope

< 2500 B.C. | 400 B.C.–170 A.D. | 1543–1648 A.D.

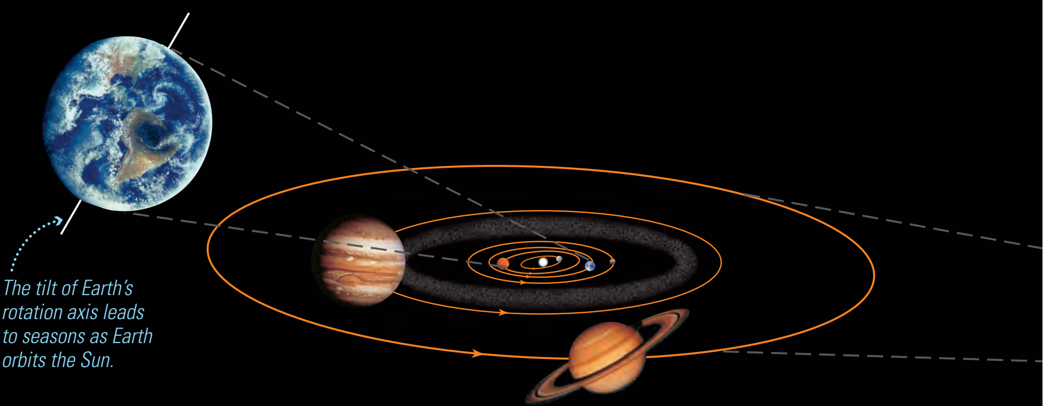
1. Ancient civilizations recognized patterns in the motion of the Sun, Moon, planets, and stars through our sky. They also noticed connections between what they saw in the sky and our lives on Earth, such as the cycles of seasons and of tides [Section 3.1].

2. The ancient Greeks tried to explain observed motions of the Sun, Moon, and planets using a model with Earth at the center, surrounded by spheres in the heavens. The model explained many phenomena well, but could explain the apparent retrograde motion of the planets only with the addition of many complex features—and even then, its predictions were not especially accurate [Section 3.2].

3. Copernicus suggested that Earth is a planet orbiting the Sun. The Sun-centered model explained apparent retrograde motion simply, though it made accurate predictions only after Kepler discovered his three laws of planetary motion. Galileo's telescopic observations confirmed the Sun-centered model, and revealed that the universe contains far more stars than had been previously imagined [Section 3.3].



Earth's rotation around its axis leads to the daily east-to-west motions of objects in the sky.



The tilt of Earth's rotation axis leads to seasons as Earth orbits the Sun.

Planets are much smaller than the Sun. At a scale of 1-to-10 billion, the Sun is the size of a grapefruit, Earth is the size of a ball point of a pen, and the distance between them is about 15 meters.

Yerkes Observatory

Edwin Hubble at the Mt. Wilson telescope

Hubble Space Telescope

1838–1920 A.D.

1924–1929 A.D.

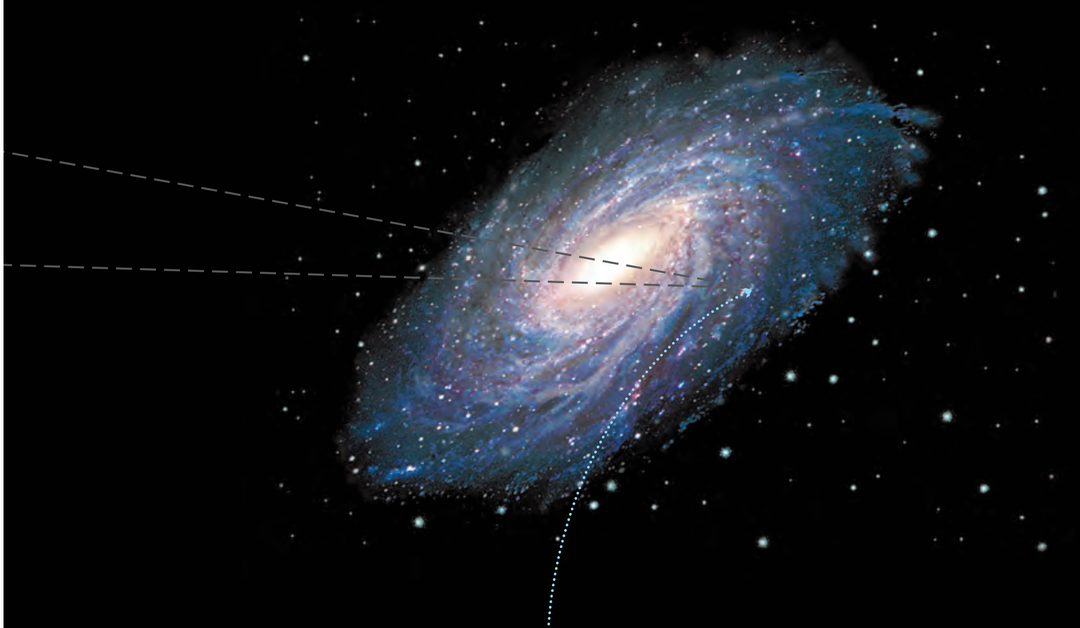
1990 A.D.–present

4 Larger telescopes and photography made it possible to measure the parallax of stars, offering direct proof that Earth really does orbit the Sun and showing that even the nearest stars are light-years away. We learned that our Sun is a fairly ordinary star in the Milky Way [Section 2.4, 15.1].

5 Edwin Hubble measured the distances of galaxies, showing that they lay far beyond the bounds of the Milky Way and proving that the universe is far larger than our own galaxy. He also discovered that more distant galaxies are moving away from us faster, telling us that the entire universe is expanding and suggesting that it began in an event we call the Big Bang [Section 1.3, 20.2].

6 Improved measurements of galactic distances and the rate of expansion have shown that the universe is about 14 billion years old. These measurements have also revealed still-unexplained surprises, including evidence for the existence of mysterious “dark matter” and “dark energy” [Section 1.3, 22.1].

Distances between stars are enormous. At a scale of 1-to-10 billion, you can hold the Sun in your hand, but the nearest stars are thousands of kilometers away.



Our solar system is located about 28,000 light-years from the center of the Milky Way Galaxy.

The Milky Way Galaxy contains over 100 billion stars.

The observable universe contains over 100 billion galaxies.